FORINTEK CANADA CORP.
presents

SCANNING TECHNOLOGY FOR THE EIGHTIES

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Opening Remarks

K.A. French, Forintek Canada Corp., Vancouver, B.C.

Welcome to another of Forintek's seminars where we will present to you the latest technology for the wood products industry.

This two-day seminar is being presented to you through the financial support of the Federal Department of Regional Industrial Expansion, under the IRDP program. Gene Smith is in the audience and will speak to you during the program; Gene, we greatly appreciate your support on these industry technology seminars.

Forintek Canada Corp. is Canada's national wood products research institute--we have laboratories in Vancouver and Ottawa and a regional office in Quebec City. Our staff of about 200 conduct research and development in all of the major sectors of the wood industry in Canada; they are also heavily involved in the development of independent data for codes and standards agencies in Canada and in the significant export markets for Canadian wood products; they devote a part of their time to preparing and presenting training programs for our industry and they have cooperative programs with various universities across Canada to help with the education of good quality young people for our industry.

A major part of our program is technology transfer. Good research requires good techonology transfer before it can become commercially useful. One of the contributions that we have been able to make to our industry is the assembly of unique combinations of people with R & D skills and industrial experience to solve technological problems, and develop new knowledge, to improve the competitive position of our industry in world markets.

For some time now, forest industry leaders across the country have expressed concern about Canada's ability to remain a dependable, low-cost supplier of wood products to the world. Higher harvesting costs, lower wood quality and diminishing supply of economically accessible wood have been documented in every region of the country. In addition, Canada is said to be the least efficient producer of lumber among the major world suppliers.

Technological innovation and technical change are some of the few remaining options that must help the Canadian wood products industry to successfully address these challenges, to its continued viability and development. One of the most promising areas of technological innovation is the application of scanning technology to the production of lumber.

During 1983 we held a series of eight seminars across Canada to discuss productivity improvement through the use of microelectronics. Industry speakers at each of the seminars identified areas where lumber recovery improvement opportunities exist in a majority of mills.

- Log trim - 2.5 percent recovery improvement opportunity
- Headrig - 3.3 percent
- Size control - 3.3 percent
- Edgers - 6.0 percent
- Trimmers - 5.0 percent.

There are numerous examples across the country where good manufacturing practice has yielded significant improvments in recovery. This must be the first step in any upgrade program that any mill undertakes. The next phase begins to involve capital improvement, and eventually advanced automation.

It is our view that about half of the recovery improvement opportunities can be achieved by good manufacturing practice and relatively small capital improvements. The remainder must be picked up through automation. The level of automation that can be achieved is very dependent on scanning, however, the industry's own assessment of the percentage of wood being processed with technologically advanced equipment today is about 10 percent. There is clearly a lot of room for growth.

In this seminar, we have brought together a unique group of people with varying backgrounds and disciplines, to present the latest in scanning technology that could be applied to the wood industry.

We have drawn on the medical field to explore the internal quality of a log. Rapid advances in the video field now open the opportunity to use video edge detection information about log diameter and length for optimum sawing solutions. With video edge detection and perhaps video laser systems, sawmillers can move towards the best possible sawing solutions for each and every log going through the mill.

Once the first cut is made it is essential that the log position be maintained for maximum lumber recovery. Studies have indicated that a variation of 1/10 of an inch can result in a loss of 5-10 percent in lumber recovery. Ultrasonic scanning systems could make it possible to automatically determine the optimum log position for maximal lumber recovery.

In boards, as in logs, there are defects which cannot be easily detected visually. Defects such as slope of grain, compression wood or tension wood, internal rot and closed splits have an adverse effect on the strength of lumber. Any technology that can identify their location can only increase the efficiency and profitability of Canadian sawmills.

The team of speakers associated with this seminar first came together last April to present an in-house seminar to the Forintek staff. Our plan at that time was to explore various fields, both outside and inside our industry, to become familiar with the best scanning technoloy that might be applied, or adapted, to our industry. The seminar was an outstanding success, and has been expanded into this two day program.

Technological renewal of the Canadian wood products industry is essential if we are to remain a dependable low-cost supplier of wood products to the world. Advanced technologies such as scanning must play a key role in permitting us to produce higher value and more market specific products in the future. Welcome to an in-depth discussion of the latest in scanning technology for the wood industry.

Opening Remarks

E. Smith, Department of Regional Industrial Expansion, Vancouver, B.C.

I'm delighted to see so many people here today because I feel very deeply the need to upgrade our sawmills. It's perhaps ironic that Canada is the world's largest exporter of a wide variety of forest products, and yet studies indicate that we are not the world's most competitive producer. We were ten years ago but we are not today. We have allowed other countries to reduce their costs, largely through automation and the use of electronics. I had the good fortune of serving in our high commission in London from 1975 to 1979 and during that period part of my responsibilities was to visit Scandinavia, spending between four and five weeks of the year there--mostly in Finland and Sweden. During that time, the Swedes and Finns were very well advanced in the use of various devices intended to make their industry more internationally competitive. It is, I think redundant to say that the forest products industry is Canada's most important sector, for unless we remain internationally competitive, all of us are going to suffer. The economy of British Columbia, and indeed of Canada, depends on a viable, efficient, internationally competitive forest industry that can get out there and compete with the best in the world.

In this regard we do have a programme known as IRDP which is undergoing a bit of a change at the moment. While our budget has been slightly cut, the government has seen fit to maintain this program because it feels that anything we can do to improve our position in world markets is worthwhile. So we will still have a program to assist you to ensure that this great industry of ours continues to prosper.

Potential Application of Medical Imaging Techniques to Wood Products

A.E. Burgess, Department of Radiology, U.B.C., Vancouver, B.C.

Medical imaging has undergone a complete revolution over the last 10 years. There has been a dramatic change from film-based X-ray imaging to a variety of digital-based imaging methods. In this paper, I will start by giving a brief description of X-ray imaging using films, then will discuss digital radiography, computed tomography, and finally nuclear magnetic resonance imaging, now known as magnetic resonance imaging (MRI). There will also be a brief mention of thermography and ultrasound.

Basic X-ray Imaging

A simple X-ray imaging system consists of a supply of X-rays from an X-ray tube and a device called an image receptor. For human radiography, the X-ray tube is operated at a potential of about 70 kV and the image receptor usually consists of a photographic film sandwiched between two layers of phosphor. The phosphors act as X-ray-to-light converters and the film acts as a data acquisition, storage, and display medium.

X-rays produce images because there is spatial variation in attenuation coefficient. Materials like water and soft tissue have a moderate attenuation; objects like bone have a high attenuation; and spongy tissue such as lungs has a very low attenuation coefficient. Unfortunately X-rays cannot be focused or redirected the way optical photons can. So this means that projection images consist of overlay of all the patient structure in the path between the X-ray tube and the image receptor.

This analog film method also suffers from two other problems. One is that there is a limited dynamic range to the imaging receptor, i.e. there is a limit to the ratio of the highest to lowest X-ray intensity at which structure contrast can be represented on the film. There is additionally a more subtle problem due to scatter radiation due to Compton scattering in the soft tissues of the patient. This has the effect of reducing image contrast and also introducing additional image noise due to statistical fluctuations.

From an engineering point of view, one of the basic limitations of film-based analog radiography is the fact that data acquisition is intrinsically coupled with data display. By that I mean that the film acts both as the data acquisition system and as the display system. This is not a problem for thin objects but becomes a severe problem for very thick objects where there is an enormous variation in X-ray attenuation. It is worth reminding you here that X-ray attenuation is an exponential function of the product of patient thickness and linear attenuation coefficient.

To put this into perspective, consider an object such as a human abdomen which is 20 cm thick and approximately equivalent to water. An object like this transmits only about one percent of the incident X-radiation at 70 kV. The transmission through a 40 cm object is only 1/100th of one percent, i.e. one part in 10^4. If the object were 60 cm thick, the transmission would be one part in 10^6. The significance of these numbers is obvious. It is not particularly difficult to radiograph thin objects, but for thick objects it becomes extremely difficult.

One final limitation of analog radiographic imaging from a wood products point of view is the time delay involved between exposing and developing the film. This limitation makes it unsuitable for on-line industrial applications. In human imaging and nondestructive testing, the film serves as a permanent, unalterable record that can be archived and, in these cases, there is in fact an advantage to using film.

Digital Radiography

With the advent of relatively inexpensive computer memory and also very high speed analog-to-digital conversion and data acquisition equipment, a number of people have undertaken extensive research into digital projection radiography.

At the moment, there are two applications in medical imaging. One is related to blood vessel imaging and is referred to as digital subtraction angiography. The other application has to do with chest radiography.

The hardware for these two applications is significantly different. For digital subtraction angiography, the image receptor consists of an electronic image intensifier that converts the two-dimensional X-ray pattern into an electron pattern which is amplified and transferred to the input of a television camera. The video signal from the television camera is digitized at very high speed and stored in a computer memory. The input end of the image intensifier is a disc-shaped surface up to 14 inches in diameter.

The important point is that the X-ray beam is rather large in two dimensions so one can think of this as an area technique. An area of the patient is imaged simultaneously in one pulse of the X-ray beam with a pulse time ranging from 1/30th up to perhaps 1/10th of a second. This area capability is useful when one is studying the dynamics of blood flow in a limited area on a patient.

The chest unit by contrast uses a line scan technique (see Figure 1). The X-ray beam is thin and fan-shaped covering a width of about 50 cm in one direction and only a few millimeters in the perpendicular direction. The image receptor consists of a long thin phosphor layer coupled to a 1,024 element photodiode array. The phosphor converts the X-ray pattern into light which is then converted into an electrical signal by the photodiodes. The electrical signal is subsequently amplified and converted to digital form.

The X-ray tube is mechanically coupled to the detector array and the two are scanned rapidly along the patient in a time of the order of one to two seconds. During this scan time, the detector array output is rapidly sampled so that a total of 1,024 samples are taken across the scan. There are also 1,024 photodiodes in the detector array so that the final picture consists of about 10^6 picture elements. The digital data for these picture elements is then stored in a computer memory.

Both of these digital imaging techniques require very rapid analog-to-digital conversion. A typical digital subtraction angiography unit uses a 512 x

512 picture element matrix which is sampled 30 times a second with 8 or 10 bit accuracy. This requires an analog-to-digital converter that can run in the 10 MHz range. The digital line scan chest unit runs at about 10^6 picture elements a second and digitizes to 12 or 14 bit accuracy because of the added dynamic range requirements.

The digital subtraction angiography technique has been a medical success because it allows very accurate subtraction of patient structure which is not changing in time, such as bone overlying the region to be imaged.

One popular application is investigation of arteriosclerosis in the carotid and vertebral arteries in the neck. The blood vessels need to be studied in a background of vertebrae and lower skull bone. It was possible in principle to do film subtraction, however, it was an extremely tedious, inaccurate process and not entirely satisfactory.

It is yet to be shown that the digital chest unit will be successful. However, the motivation for trying it is clear. Chest film radiography has always presented an unsatisfactory compromise because the physical nature of the chest. The central part of the chest consists of the heart plus large blood vessels that are relatively opaque to X-radiation, while on either side there are two lung fields which are relatively transparent to radiation. Given the limited dynamic range of film, this has meant that the X-ray contrast has to be deliberately reduced to allow simultaneous imaging of both the central and lung fields.

One might think that a simple solution would be to make two radiographs, one optimized for the mediastinum and one optimized for the lung field. Unfortunately, chest radiographs represent about 60 percent of all medical radiography. By going from one to two films, the total radiation dose of the world population because of medical procedures would be greatly increased and secondly, the amount of film to be stored would be nearly doubled.

Neither of these considerations is a trivial one. The aim of the digital chest unit is to take advantage of the very high dynamic range capability of electronic imaging systems and to use some advantages inherent in digital display systems.

Digital Line Scan Of Logs

I have used the computed tomography machine at UBC to do digital line scans of logs and some examples of these will be discussed.

One example is shown in Figure 2 (plate 1). It is a piece of green hemlock about 17 inches in diameter with two knot structures that are easily visible. The quality of this image is very high. It took two seconds to produce and was done at a tube voltage of 125 kV with a 512 element detector system. The detector array was oriented across the log and was scanned rapidly from one end to the other with a total of 256 samples from one end to the other.

With current technology, it would be feasible to use this technique for scanning wood products or logs in thicknesses of up to at least 50 cm.

Computed Tomography

Most people would agree that computed tomography (CT) has been the most significant advance in X-ray imaging since the discovery of X-rays.

The principle is deceptively simple. Given an object of unknown internal structure, one passes an X-ray beam through the object from a very large number of directions, makes transmission measurements at each projection angle and then combines all of the data using a computer to make the best possible estimate of the internal structure given the projection data.

The fundamental mathematical solution to this problem was developed by Radon in 1916. The X-ray CT technique was first proposed by Cormack in 1962 but was not implemented. Hounsfield in 1968 independently developed the technique which resulted in the EMI head scanner which was first sold in 1972.

The enormous clinical advantages of this machine were immediately obvious and by 1976, CT was a billion dollar market. Cormack and Hounsfield shared the 1979 Nobel Prize in Medicine for their contributions.

The basic strategy of CT scanning is illustrated in Figure 3. The X-ray tube produces a thin fan-shaped beam which is measured by an array of detectors. The X-ray tube and detectors are mechanically coupled together and rotate around the patient. In a typical configuration, there are 512 detectors in the array and each detector is sampled once every 8 milliseconds.

The detector commonly consists of a fluorescent crystal such as bismuth germanate (BGO) connected to a photodiode. The crystal converts the X-ray intensity to a light signal and the photodiode converts the light signal to an electrical signal which is subsequently amplified and converted to digital form. There are some severe technical requirements in order to successfully do computed tomography.

The following discussion will be based on medical clinical needs where one would like to image objects down to a size of about 1 mm. In order to do this, the mechanical configuration of the detector and X-ray tube must be accurately positioned to within 25 microns (1/1000th of an inch). The X-ray tube must be capable of a very high output and the detector system must have a dynamic range of 19 bits, i.e. a factor of 5×10^5 between the lowest and highest intensity values that it can handle. This 19 bit signal then has to be digitized at a rate of about 100,000 samples per second.

I have used the CT scanner at UBC to scan a number of logs and an image of a green hemlock log is shown in Figure 4 (plate 1). As you can seen, the log is not completely round because unfortunately, in its original form, it was too large to fit into the gantry of the scanner. It was necessary to saw two faces to get it through the gantry. A knot is easily visible in the eight o'clock position in the image. The sapwood is also easily visible as a bright circular annulus in the outer part of the log.

There are also two circular overlays in the image labelled 1 and 2. Region No. 1 is in the sapwood and gave a mean CT number of 104 which means that its attenuation is about 10 percent higher than that of water. Region No. 2 is in the heartwood and the mean CT number for that region is -536 which represents an attenuation of about 47 percent of that of water.

The CT scale starts at -1000 for air, proceeds up to zero for water, and continues to higher values for materials of higher density or atomic number. A sample of the sapwood was cut from the log and placed in water to estimate the physical density. The sapwood just barely floated which suggested that the physical density was 0.97 or 0.98.

There have been industrial applications of CT, mainly using radioisotope X-ray sources rather than X-ray tubes. There are occasionally good technical reasons for using an isotope. Some examples of industrial applications include scanning of wood pilings, solid fuel rockets, as well as a prototype package scanner for the U.S. military.

One unfortunate feature of current CT scanning from a product quality control point of view is the rather slow operation. The scanner at UBC is one of the fastest in the world and requires about two seconds scan time to produce an image. This is obviously too slow for production line use. However, a prototype cardiac scanner has just been developed that operates at 15-30 slices/second for limited periods of time with image reconstruction done after data acquisition is completed.

For on-line industrial application, it would be necessary for the projection reconstruction computing system to keep up with the data acquisition system. The projection reconstruction is most easily done using array processes and such high speed reconstruction is not technically out of the question.

Before leaving X-ray imaging, it would be worth mentioning the problem of statistical fluctuations (also known as noise). Photons are quantized and arrive at the detector in a random manner analogous to raindrops falling on a sidewalk. In a typical projection radiograph, only about 10,000 X-ray photons are used for each square millimeter of image area. Since the photons obey Poisson statistics, there is a statistical variability with a standard deviation equal to the square root of the number of photons, in this case 100.

This standard deviation as a proportion of the total number of photons is therefore equal to one percent. The light from these photons is spread out by the intensifying screen over regions the order of 0.5 mm in diameter so the fluctuations in X-ray flux show up as a mottled appearance that can be seen under careful investigation on the radiograph. In fact, radiographic system speed is carefully selected to ensure that these statistical fluctuations are at about the threshold of visual perceptibility. This is analogous to adjusting the gain on an electronic amplifier to the point where the noise is just barely discernible.

These fluctuations are important because they represent a fundamental limit on one's ability to acquire information from the images. The effect of this noise is shown in a famous set of images produced by Albert Rose illustrated in Figure 5. This shows a woman's face produced with a progressively decreasing number of photons. With a large number of photons very fine detail is visible but as the number of photons is reduced detail is harder and harder to see.

In designing any X-ray imaging system, one must be acutely aware of this noise problem and ensure that enough photons are going to get through the object being radiographed in order to produce useful images. As the objects become thicker, the transmission of X-rays rapidly decreases and one must therefore increase the intensity of the X-ray source or the exposure time in order to get adequate photons transmitted to the detector. The image receptor system including the X-ray-to-light converter, the light-to-electronic converter, and subsequent amplifying system must be of very low noise design to avoid introducing any additional noise into the measurements.

Also, dynamic range requirements can introduce rather severe technical problems because one is trying to accurately measure signals in the microvolt to millivolt range in the regions of material where there is low transmission, while measuring signals in the order of one to 10 volts in regions of high transmission.

There are clearly many problems that one has to deal with in designing X-ray imaging systems for on-line process control for wood products. Fortunately there are a large number of research and engineering groups exploring a large number of possible ways of digital X-ray imaging for medical applications and their results can be used as a guide for design of wood products scanning devices.

Magnetic Resonance Imaging

We now come to another revolution in medical diagnostic imaging. About 10 years ago, it was proposed that the nuclear magnetic resonance (NMR) technique could be used for producing images of biological material. I don't have time here to go into detail of the NMR method and can just briefly outline it.

To do NMR, one needs a high magnetic field (Figure 6) that is also very homogeneous over the region to be imaged. For medical applications this means magnetic fields in the order of 1000 gauss to 1500 gauss, uniform to one part in 10^5 over regions of one metre in diameter. There are a number of nuclei that have a net magnetic moment (this means that they behave like tiny bar magnets). The isotopes of particular interest for medical imaging include hydrogen (i.e., isolated protons), fluorine-19, and phosphorus-31 because they are all relatively abundant in the body.

Now consider these nuclei as tiny bar magnets. In the absence of a magnetic field, these bar magnets are randomly oriented in space. When the patient is placed in a high magnetic field, they align either parallel or anti-parallel to the field with a slight excess parallel. This is referred to as net magnetization. The magnets are not precisely aligned with the magnetic field but rather they precess rapidly about the magnetic field in a manner similar to gyrating tops.

The frequency of precession depends on the nature of the nuclei and the strength of the magnetic field. For protons in a 1000 gauss field, this precession frequency is 4.2 MHz. If these precessing nuclei are irradiated with a high energy pulse of 4.2 MHz electromagnetic radiation, they are perturbed from their equilibrium precessing positions. After the pulse is finished, the perturbation dies away exponentially giving off a very weak electromagnetic signal at the resonant frequency. This can be detected using a sensitive radio receiver. Hence the name nuclear magnetic resonance.

Nuclei in a magnetic field can absorb energy in a resonant manner. Suppose we would like to obtain a map of the distribution of protons in an object. In order to do this, we have to provide a spatially varying perturbation on the main magnetic field so that the resonant frequency depends on position in the patient. This is done using secondary field gradient coils so that a change of few percent in resonant frequency occurs from one side of the object to the other. This is a one-dimensional gradient so that all of the nuclear spins along a line through the object have the same resonant frequency.

So with a field gradient in one direction, a projection profile is obtained in the perpendicular direction. The direction of the gradient is then rotated in increments to cover a range of 180-degrees and the data intensity profiles for all of these projections is then used to reconstruct the map of protons in a slice through the patient. There are other more subtle ways of producing two- and even three-dimensional maps of proton density distribution in the patient.

There are two other exciting aspects of NMR that do not have an analogy in X-ray imaging. These are measurements of the relaxation times, T_1 and T_2, that provide information about the chemical environment in the vicinity of the protons. It is these features that have caused great excitement in diagnostic medicine.

The green hemlock was imaged using the Picker magnetic resonance scanner at the UBC hospital. An example scan is shown in Figure 7 (plate 1). This is a cross-section slice using a "spin-echo" pulse technique through the same knot region imaged in the CT scan slice of Figure 3. Clearly, the image is not as good as that of the CT scan; however, we have no reason to believe that we had optimized the magnetic resonance scanning method in the short time the scanner was available. Also note that the core of the knot gives a weak signal because there is little free water.

To provide another basis of comparison, the CT scan took two seconds to do while the NMR scan took 13 minutes. Magnetic resonance imaging is inherently a slow process because only one projection angle can be done in the approximately one second relaxation time of protons in solutions. So even under the best of circumstances, one can expect to spend on the order of two to four minutes to acquire a magnetic resonance cross-section image.

There is the possibility of increasing measurement throughput by using multiplexing techniques. During most of the imaging time for a single slice, the machine is simply waiting and this "dead-time" can be put to good advantage by doing measurements on other slices. In principle, one can interleave measurements of up to 16 slices.

Taking this multiplexing into account, one still must allow about 15 seconds for each slice to be done. Given these constraints, magnetic resonance imaging could be used to make measurements of samples from production line but could not be used realistically for on-line process control.

Summary

Three medical imaging techniques have been described, X-ray digital radiography, X-ray computed tomography and NMR tomography.

The digital radiography method is the easiest to adapt to wood products scanning. Design details and difficulties in implementation depend on the application. If the scan width is narrow (up to 30 cm wide) an electronic image amplifier can be used together with a self-scanned diode array and eight-bit analog to digital conversion can be done at video rates (5 MHz). This design would be adequate for long, narrow objects run through the scanner longitudinally. Any other geometry (e.g. long objects run transversely) would require a more complex multi-detector design. The number of design permutations and combinations is too great to deal with here.

X-ray CT application possibilities may be restricted by scanning speed requirements and object size. There are two basic limits - one has to do with the number of X-ray photons transmitted by the object during the scan of one slice. One must have enough transmitted photons to obtain a good signal-to-noise ratio in the image. The photon flux is determined by X-ray source, object, and detector properties and is also proportional to the time used to image the slice. The X-ray photon flux problem is a fundamental physical limitation.

The second limitation has to do with data acquisition and image reconstruction. There is a speed limitation based on current digital technology. Present (medium priced) computer technology would limit scan rates to the order of one slice per second. This situation can be expected to improve. Again there are a large variety of possible designs for X-ray CT hardware depending on application considerations.

Present NMR imaging methods are inherently slow. After perturbing nuclear spins, one must wait for times in the order of one second before repeating the procedure. With this constraint, times on the order of 100 seconds are needed to produce an image. There is an experimental method that produces an image in 30 milliseconds but the signal-to-noise ratio is presently very low.

NMR imaging technology may be useful for wood production measurements sometime in the future. However, for the moment its application is limited to sample measurements.

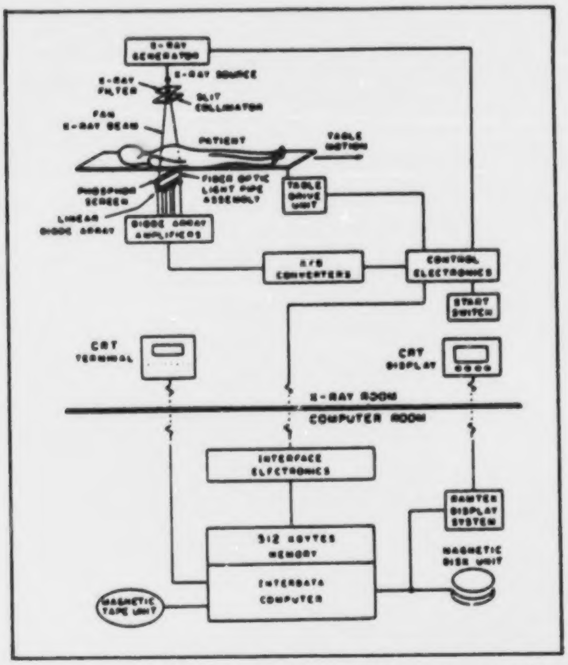

X-RAY GENERATOR
X-RAY SOURCE
X-RAY FILTER
SLIT COLLIMATOR
FAN X-RAY BEAM
PATIENT
TABLE MOTION
FIBER OPTIC LIGHT PIPE ASSEMBLY
PHOSPHOR SCREEN
TABLE DRIVE UNIT
LINEAR DIODE ARRAY
DIODE ARRAY AMPLIFIERS
A/D CONVERTERS
CONTROL ELECTRONICS
START SWITCH
CRT TERMINAL
CRT DISPLAY
X-RAY ROOM
COMPUTER ROOM
INTERFACE ELECTRONICS
RAMTEK DISPLAY SYSTEM
512 KBYTES MEMORY
MAGNETIC DISK UNIT
INTERDATA COMPUTER
MAGNETIC TAPE UNIT

Figure 1. Diagram of the Pittsburgh CER line scanned system (courtesy of Don Sashin, University of Pittsburgh).

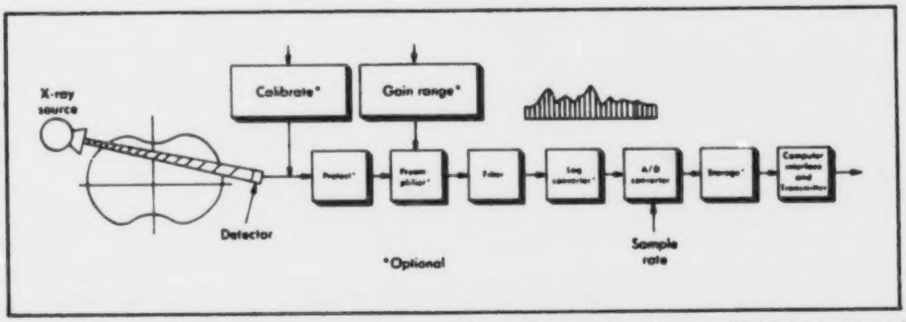

X-ray source
Calibrate*
Gain range*
Detector
Preamplifier*
Filter
Log converter*
A/D converter
Storage*
Computer interface and Transmitter
Sample rate
*Optional

Figure 3a. Block diagram of DAS flow for CW system (filter type). CT scanner.

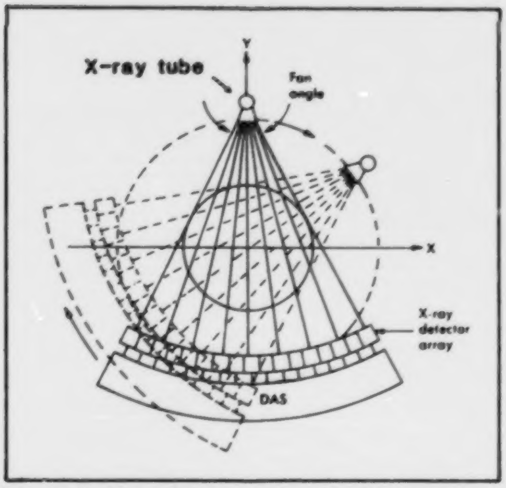
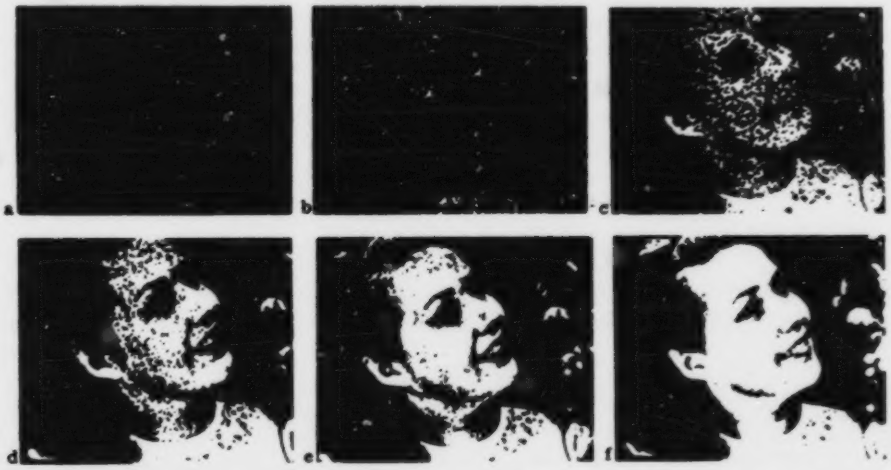


Figure 3b. X-ray tube and detector array (+ data acquisition system) are mechanically coupled. They rotate together around the circular region to be scanned. The detector outputs are sampled about every 1° increment over a 360° angle of rotation.



Picture	Number of photons	High-light brightness, foot-lamberts
a	3×10^3	10^{-6}
b	1.2×10^4	4×10^{-6}
c	9.3×10^4	3×10^{-5}
d	7.6×10^5	2.5×10^{-4}
e	3.6×10^6	1.2×10^{-3}
f	2.8×10^7	9.5×10^{-3}

Figure 5. Series of pictures used in evaluating the quantum efficiency of the eye.(R-4)

Illustrates the effect of decreasing signal/noise ratio on detail visibility. (From: A. Rose, Vision-Human and Electronic, Plenum Press, N.Y., 1973).

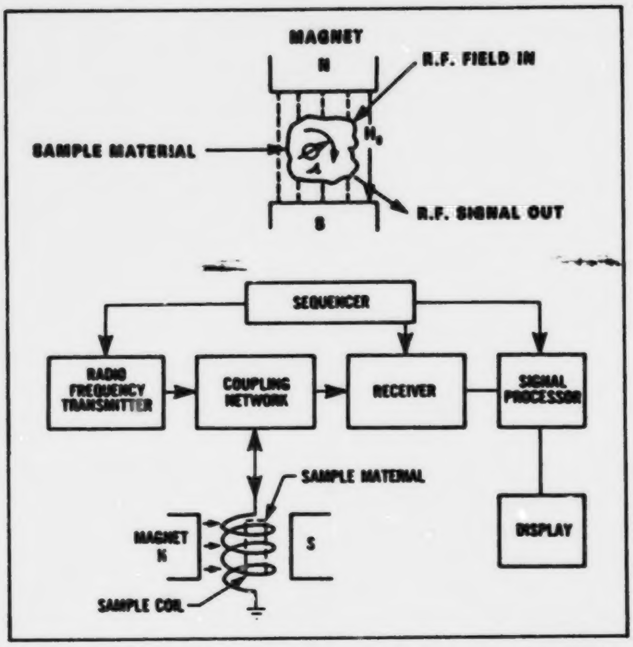

MAGNET
N
R.F. FIELD IN
SAMPLE MATERIAL
H0
R.F. SIGNAL OUT
S
SEQUENCER
RADIO FREQUENCY TRANSMITTER
COUPLING NETWORK
RECEIVER
SIGNAL PROCESSOR
SAMPLE MATERIAL
MAGNET N
S
DISPLAY
SAMPLE COIL

Figure 6a. The basic NMR apparatus for such a measurement consists of five subsystems (1) magnet, (2) radio transceiver, (3) sequencer, (4) signal processor, and (5) display.

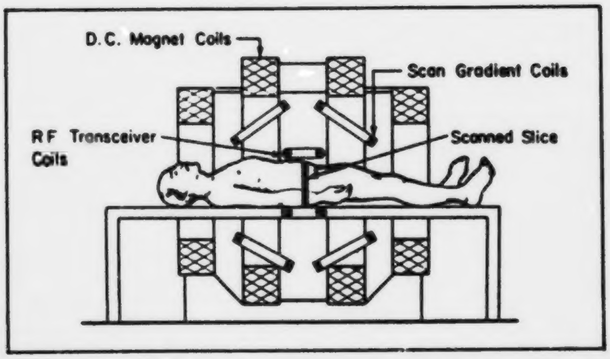

D.C. Magnet Coils
Scan Gradient Coils
RF Transceiver Coils
Scanned Slice

Figure 6b. Physical diagram of wholebody NMR scanner.

Towards Automatic Sawlog Defect Detection Using Computer Tomography

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In a computer tomography x-ray scan of a log, one can easily discern the tree's growth rings, knots and areas of rotten wood. In this paper, we describe an image interpretation system which can locate and identify these same features automatically. The data describing where the rot and knots are hidden within a sawlog can by used, in computer-controlled milling, to obtain the maximum lumber yield.

Introduction

A major problem in milling trees into lumber has always been that nothing is known about where knots and rot are buried inside a log until it is cut. Now, with computer tomography x-ray imaging techniques, the potential exists for sawing decisions to be founded on advance knowledge of each log's internal structure. A computer tomography image, CT-scan, of a log nondestructively provides an amazingly detailed cross-sectional view of what is inside it.

Figure 1a (plate 2) is a CT-scan of a hemlock log, approximately 40 centimetres in diameter. Although the important features in the CT-scans are readily discernible to the human eye, our goal has been automatic interpretation of the images. Computer interpretation of the images combined with automated cutting is in fact essential if information about the inside of the log is to be used. There is simply not enough time for a person to make sense of the data at the rate of three logs per minute common in many sawmills. Computer-controlled sawlog cutting is already in widespread use in sawmills, but the cutting decisions are based only on the log's external dimensions as ascertained either by photocell sensors or, more recently, digitized vidicon images.

By combining a sequence of interpreted CT-scan slices to form a complete three-dimensional model of a log in which the location and size of knots, and the location and extent of rotten regions is described, it will be possible to significantly increase the log's lumber yield.

A significant aspect of lumber yield is not just the amount of wood produced, but the quality of the wood as well; and a major factor affecting quality is the number and size of the knots which each board contains. Cutting a log so that some boards have a lot of knots, while leaving others with none, results in a higher yield than a random distribution of knots throughout. Another factor influencing quality is the presence of rot. So rot and knot detection are two of the major goals of the CT-scan interpretation process.

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Image Characteristics

CT-scanners produce density maps which generally are displayed as images of varying intensity. In Figure 1a (plate 2), the dark areas represent wood of low density, and the light areas that of high density. It has a resolution of 256 by 256 points. Industrial scanners are now becoming common and have been applied in a variety of domains (Hopkins et al., 1981).

In the CT-scans, the growth rings are clearly visible because the fast summer growth produces lower density wood than the slower winter growth. High density (light colored) regions generally indicate knots, but as seen in the figure some high density regions are found which are not due to knots. These present a problem for any algorithm based on the idea that knots can easily be distinguished by their density. Frequently the knots are buried inside the tree because they are remnants of branches which, as the tree aged, fell off and became surrounded by the tree's continued growth. Since the knots result from branches, they generally have a roughly elliptical shape, and this helps to distinguish them.

Rot deteriorates the wood in a way which is reflected in a reduction in its density. Serious rot is easily distinguished by its very low density. Rot in its early stages shows up as specks of low density intermingled with specks of normal density. This appears as a general degeneration, or breaking up, of the growth ring pattern.

Image Interpretation Hardware and Algorithms

The image interpretation algorithms have been developed on hardware consisting of an International Imaging Systems Model 70F, a video-rate image processor (Ullmann, 1981) tied to a host VAX 7/50. The IIS Model 70 contains a special look-up table and pipeline processing hardware, and these features make it possible to convolve an image with a sizable mask approximately two orders of magnitude faster than with the host machine alone. Every attempt has been made in designing the interpretation algorithms to make use of these fast convolutions.

The interpretation process essentially consists of two parts, one for knots and the other for rot. With minor exceptions, remaining regions represent good wood. The first stage in knot identification is to smooth the image with a two-dimensional Gaussian mask, chosen so that it will substantially blur the image. This removes some noise, but more importantly it reduces the high density values created by growth rings without lowering the density values within the knots (except near the knot boundaries). Smoothing therefore enhances the density difference between knots and good wood. Without smoothing, the density of the slow growth part of a growth ring may approach that of a knot. Because growth ring regions alternate high and low density, their average density, as computed by smoothing, is less than the average density of a knot.

A histogram, the green curve in Figure 1b (plate 2), of the image reveals a density distribution with two peaks. The small "tail" in the high density range corresponds to knots, the middle peak to good wood, and the left peak to rot and air. The height of the peaks varies with the size of the log (small logs have more air around them), and the number of knots. In histograms of logs with large knots, a third peak appears in the high density range. The good wood peak often has a plateau extending into the high density range representing unusually high density good wood.

The peaks are separated by first taking the third derivative of a smoothed version of the histogram. The zeros correspond to its points of maximum absolute curvature. The ones having a positive second derivative represent dips in the histogram, and are natural places to subdivide it.

In Figure 1b (plate 2), the blue, red and yellow curves correspond to the first, second and third derivatives, respectively. The vertical bars show the points where the program chooses to subdivide the histogram. This method of finding "edges" in the histogram is an adaptation of the two-dimensional edge-detection procedure described in Marr and Hildreth (1979).

While use of the second derivative would have more closely corresponded to their method, here we want the boundary of an edge, rather than its midpoint, so the third derivative is used. Once the peaks are isolated, the ratio of the integral under the high density peak to that of the middle peak yields a rough measure of the relative amount of knot to good wood. In addition, holes in the wood are easily spotted because their density is that of air.

Using the low density boundary of the knot peak as a threshold isolates those points which most probably belong to knots. These points usually occur in clusters, but they do not necessarily form solid areas. The clusters are merged into solid regions by iterative application of a locally parallel operation which can be expressed as a sequence of image convolutions. This process always produces convex regions with at most eight sides. They provide a relatively concise representation and a workable approximation to the roughly elliptically shaped knots.

In essence, a region is expanded to fill a new pixel whenever two of that pixel's neighbours belong to the region and the three-pixel group forms a right angle. A similar technique shrinks and eliminates isolated groups of two or three pixels.

Once the clusters of high density points have been amalgamated into solid convex regions, their shape is used to distinguish the ones due to knots from those due to unusually high density patches of good wood. The criterion indicating a knot is the presence of an elliptical region with its major axis pointed towards the centre of the log. To test for it, the centre of mass, principal axes and moments of inertia (Goldstein, 1950) of the region are computed. The principal axes and moments define an inertially equivalent ellipse; and the ratio of the moments along the principal axes provides a measure of the elongation of the ellipse, and hence an indication of the likelihood that the region is a knot. Another indication is a small angle occurring between the major principal axis and a line from the centre of mass to the log's centre.

While rot in its advanced stages can easily be distinguished by its very low density, less severe cases are noticeable in CT-scans only because they begin to destroy the growth ring pattern. Their visual texture is different from that of healthy growth rings. The procedure which distinguishes this kind of rot tests the uniformity of orientation of short edge elements. Where there is good wood, and good growth ring structure, the edge elements in any small region are oriented in the same direction; but where rot is present the edge-element orientations are much more randomly distributed.

From the original image, oriented edge elements are obtained by the Marr and Hildreth (1979) edge detector, and are stored in a separate edge-element image. This new image is then convolved with a series of masks to establish the uniformity of the edge "flow" at each point in the image. The procedure computes the number of edge elements occurring in each of four directions, finds the maximum, and takes the ratio of this to the total number of edge elements found within the mask. The ratio indicates the degree of uniformity. Points combining low density with low flow uniformity are counted as rot. Clusters of such points can be merged into convex regions in the same way as for knots.

Results

The system has worked well on a limited set of test CT-scans. Figure 1c (plate 2) shows the final interpretation of the scan from Figure 1a (plate 2). Yellow areas represent rot; blue, air; red, knots (when the associated number corresponding to the knot's elongation factor is less than 0.3); and the rest is good wood. The test samples have primarily been hemlock. Some cedar and pine have been examined, and other species will be tried soon.

Generally, there does not appear to be substantial variation in the CT-scans across species, but it may well be the case that the algorithms can be tuned to take species-specific traits into consideration. The complete interpretation process takes approximately four minutes. The x-ray time combined with that for image reconstruction takes about a second.

Cracks are one log defect which CT-scans may not help to discover prior to milling. A board may split apart once it is cut, but the structural weakness which leads to the split cannot be seen in the CT-scan because the rest of the log is holding the wood together.

Variations in water-content present a problem because the density of wood is close to the density of water. The density difference, however, is enough so that the interpretation is not substantially affected. Figure 1d (plate 2) shows a CT-scan of the same log scanned at the same location as in Figure 1a (plate 2). The only difference is that the scan was taken immediately after the tree was cut; whereas, the scan from Figure 1a (plate 2) was taken two months later, after the log had dried. Figure 1e (plate 2) is the interpretation of Figure 1d (plate 2), and is very similar to the previous interpretation (Figure 1c, plate 2).

Conclusion

We have described an image interpretation system which identifies knots, rot and holes in CT-scans of logs. Each scan is a two-dimensional cross-sectional probe into the log's internal structure. After analysis by this system, a set of scans taken at intervals along a log could be composed into a three-dimensional model which could then be processed to determine the logs's optimal use.

While the interpretation process is successful, several problems remain. Perhaps the most severe is that the current method is too slow for the demands of a sawmill. Others are more related to CT-scanning itself. Medical scanners generally have a maximum allowable object diameter in the 55 cm range, and there are some limitations on how much it can be extended.

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References

Goldstein, H. 1950. Classical Mechanics. Addison-Wesley.

Hopkins, F.F., I.L. Morgan, H.D. Ellinger, R.V. Klinksiek, G.A. Meyer, and J.N. Thompson. 1981. Industrial tomography applications. IEEE Transactions on Nuclear Science. Volume NS-28, No. 2.

Marr, D. and E. Hildreth. 1979. Theory of edge detection. A.I. Memo 518, Massachusetts Institute of Technology.

Ullmann, J.R. 1981. Video-rate digital image analysis equipment. Pattern Recognition 14:305.

Scanning for Log Bucking

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When I first got involved with log scanning and using computers for bucking logs there were some simplified models being used for representing log shapes to computers.

Theoretical Log Models

- Cylindrical
- Truncated cones
- Truncated cones with arc sweep

Features in common:

- Square ends
- Circular cross-section
- Constant quality throughout

The first model is the treatment of a log as a constant diameter cylinder. This is obviously an over-simplification but was considered close enough for it to be used in some early processes, notably on Chip-N-Saw systems.

The next step up in trying to model a log was the use of the truncated cone approach. This was very popular especially among those who were trying to mathematically calculate the best ways of sawing, such as full taper, half taper, Best Opening Face, etc. In an attempt to represent sweepy logs the next step was to add a curve to the models, usually demarked by radius of curvature.

Real Logs

What we had at the time we were putting together the new Alberni Products Division mill was a general belief among control system suppliers that logs could be treated as straight truncated cones. Unfortunately, I soon discovered that logs weren't all that cooperative in fitting to the model.

When you do log bucking in the real world, you find the ends aren't even flat. When logs are cut down in the bush the butts have undercuts and pull out slivers from the stump as they fall. Unfortunately length measuring photo-cells and diameter scanners have difficulty ignoring them.

Ends bucked on a slant will give different lengths depending on which way they fall and how hight the photo-cells are. You can have as much as six inches variation, easily.

Remember our cylindrical model? One fact ignored in nearly all optimizer systems, is that logs aren't even all circular in cross-section. Most logs are not perfectly straight. As they grow, the soil under them shifts, and they bend as they try to re-attain the vertical. These shifts are not constant over the decades, so sweep is often abrupt and in more than one place.

Log Quality and Internal Defects

A simplified approach to log optimization treats logs as if they were of constant quality throughout. Unfortunately, however, logs do have their problems. Logs very often have a defect the operator can see very easily, especially if it's at the leading end. So what can he do with it? Depending on the mill, and on the quality of the rest of the log and how far he figures the rot goes in, he could cut off the bad part or make a short section for log grade cuttings, or he could make a longer piece where the lumber could be trimmed back at the trimmers.

So here you can see where people come in. Most of our operators aren't very good at judging distances or making accurate value calculations in milliseconds, but they are a heck of a lot better at guessing what's inside a log than a bunch of photo-cells are, and in addition to defects, they can even see what quality of log they are probably dealing with.

Bucking Solution Parameters

- Allowed lengths

  a. physical mill limits
  b. sales constraints

- Preferred lengths

  a. verbal instructions
  b. written cutting program sheet
  c. weighting by price in scanning system's price tables

- Log quality

  a. merch market restrictions
  b. grade cutting
  c. quality change along length

- Diameter

- Sweep

  a. sweep removal
  b. recovery gain vs. productivity loss

- Defect

What are some of the parameters we use in deciding where to buck logs? When figuring out how to buck a log the first constraint we run into is what the mill can actually handle. In other words, what will fit between the bumpers and not fall between the chains.

The next thing is, what lengths can you actually sell? Many mills find that sales for odd length boards are very limited. An important consideration is that some lengths in a product line sell for more than other lengths do. There are several ways that the mill manager's preferences can be made known to the bucking operator.

- First, he can pass his instructions along verbally. For example, "Hit 20's".
- Second, a written list of preferred lengths can be posted in the operator's booth. This could specify the reasons why certain lengths are wanted and the type of log to get them from.
- Thirdly, specific bucking solutions could be calculated from a price look-up table by a log bucking scanning system.

Another parameter we should use is log quality. When you make a sales contract, one of the things specified in the agreement is the grading rules to be applied to the product. This may vary from a standard rule such as R List Dimension to a unique listing of all the characteristics demanded.

Most orders that I've seen do require that certain percentages of the total must be in specified lengths and that only a limited percentage of the total can be in the lower grades. Any excess of bad lengths and low grades that develop must be sold somewhere else or discounted, usually at a fraction of what they would go for if they were on order.

What you can do in this situation is to cut several orders at once so that wood of a quality too low for one order might fit into another. But, very often the lengths required for the orders might be different from each other. This means that to get the most money out of the logs, you have to put the right quality logs into the right lengths.

In our mill, we cut high quality, small knot wood into 10's and 13 foots for the Japanese markets, whereas the North African order we have allows some lower grade wood, but wants 16's and longer.

With the high cost of logs on the West Coast, we are concerned with getting as much high grade material out of the logs as we can. A log may vary in quality down its length, from a shakey and brashy grained butt, through a deep clear mid section, to a knotty top. By separating each of these sections into the appropriate lengths for their grades, we can greatly increase the value of the end products developed.

Another factor used in the bucking decision is the log diameter. This is something you can measure in most scanning systems. You can then use it to calculate decisions through price optimizations. It can be shown by a program like SAWSIM that bucking a sweepy 20 foot log in half can almost double recovery. Even as little as two inches of sweep can have a dramatic effect on recovery.

Logs with abrupt bends can be bucked into short, straight sections fairly easily by cutting at the bends. Moving the cut point a couple of feet either way will have minimal effect on recovery, yet it may have a large impact on the value of the lumber extracted. Another thing you may find on the belly of the bend is 'compression wood' which is the latest bane of the export market.

Crooked logs are also hard to handle. A log which is too sweepy can be hard to balance or hold onto, and it can provide a large twisting leverage when it is fed into saws or chipper heads.

So why not buck everything as short as possible? Well, usually there are premiums paid for long lumber, and if your headrig uses time for loading and turning logs, the longer the average log length, the greater your speed of production. For example, on our log quad it takes about 22 seconds to cycle a 26 foot log, and 32 seconds to do two 13 foots. This means that cutting all our 26 foot logs in half would reduce our production rate by about 40 percent on these logs.

Defect is one of the most difficult things for current scanner tchnology to detect, but it's very apparent to the trained eye. The effect of defect depends on the type of defect and its extent. Many grades allow some decay, but too much just crumbles into nothing.

Splits in the hearts of logs are called shake. It lowers the grade of the boards that contain it. Too much and the board falls in half. There is heart shake which is a split through the heart, and there is ring shake or water shake which follows the rings and is very much more damaging in most cases.

Then there is damage caused in falling. This can range from a complete shattering to an almost invisible falling break in the middle of a log, to a mild stump pull, where fibres are pulled out by the stump in falling. This can be easily bucked off. All of these things may say to the operator, "Ignore the stuff you see up there on the screen. Chop this off over here instead".

Scanning

Length Scanning Methods

- Diameter scanner and chain pulser
- Length photo-cells and horizontal array (vernier)
- Length photo-cells and chain pulser
- Log end distancing (nozzler)
- Length information from whole log scanner

Now lets take a look at the scanners we could use. The first and most obvious thing you'd like to know is the log's length. As you can see from this list there are several simple-looking ways of going about this. A very straightforward looking way is to put a diameter scanner in the way and clock the log through a chain. The problem is, they slip.

Another way that used to be sold is to move the log through a conveyor with a bunch of photo-cells across it. At the end of the conveyor is a short section of photo-cells very close together. When the end of the log enters this 'vernier' section, the chain is moved until the next photo-cell on the trailing end of the log is unblocked. This determines the log length to the resolution of the Vernier. The problem with this method, is that the critical photo-cell might be permanently blocked or out of line.

The next way mentioned is to use fairly widely spaced photocells across the conveyor and a pulse counter (called a clock) on the chain. This method gets a coarse reading of length from the number of photo-cells blocked, then as we move the log we count pulses from the unblocking of a photo-cell at the trailing end until we block another one at the leading end. We then subtract the pulse distance from the distance between the photo-cells to get our length. Problems encountered would include photo-cell blockage and log slippage.

Next on our list is a pair of sensors usually mounted on the sides of a cross transfer deck. They use a distance measuring system to tell how far the ends of the log are from the sensors. Then the log length is the distance between the sensors minus the distances to the log ends. The problem with this system is that the beams from the sensors have to hit the log on its ends. If there is a hole in the end, or the log sweeps out of the field of view, or something else (such as the end of a longer log) sticks in the way, you'll get the wrong length.

The last method I'll discuss is getting the log length from a whole log scanner, such as a video system or by pulsing transversely through a light curtain. Here the problem is that these systems gather information over a much coarser length interval than the other methods do. For good log bucking the length resolution must be as fine as possible.

Diameter Measuring Methods

- Optimux-type PC array or similar
- Rema scanner
- Light curtain on transverse conveyor
- Moving scanner with stationary log
- Video whole log snapshot

At our mill, and at our earlier installations at Somass, we use Optimux diameter scanners across our conveyors to measure log scale. These are photo-cell arrays with sources on one side and detectors on the other side which are multiplexed to avoid cross-talk. They can give diameters with a resolution of one tenth of an inch.

Other scanners use a light source, either stationary or moving, and a light detector (either a photo-cell array or a camera) to measure log diameter by reflected light. One of the more successful of these is the Rema scanner which detects the points when a moving laser light line first strikes one edge of log, then falls off the other side.

These methods mentioned up to now use a pulse encoder on the infeed chain to determine where each diameter was measured. Something to note is, if you want diameters for your optimization, you need a conveyor system which is twice as long as the longest log you are ever going to get. Another problem is that they are very unreliable at measuring sweep.

On many logs, the diameter information may be of little value unless you also include the sweep. Unfortunately, sweep is very hard to measure in the conventionally conceived Endo-scanner installation because of log transportation difficulties.

The first problem with using a conventional diameter scanner is that logs tend to lie flat in the conveyor. Therefore, vertical diameter scanners don't sse it. This means that an horizontal array should be used, which is no problem for the element above the conveyor, but poses great survival problems for the element below.

The next problem is that logs tend to rock and roll as they run over any irregularities in the conveyor, such as cut-outs for diameter scanners. It has been suggested to have a flat back belt to use as a background, and this may work, but much of the time belts need small rollers underneath so they don't stick, and even small lumps will cause a log to pitch if it's not perfectly stable already.

Sweep

What are some diameter scanning systems that will give us sweep?

One possible method for getting sweep information is to move a log transversely in lugs up an incline through a photo-cell light curtain. This would have an array of photo-cells on say four inch centres across a wide sloping deck looking up perpendicular to the chains. A pulse encoder would be mounted on the chain drive. As the log is moved sideways through the light curtain, the value of the encoder would be read as each photo-cell becomes blocked and unblocked, giving the diameter and sweep along the entire log. Problems to be encountered by this method would be rocking of the log as it moved, and the tendency of chains to 'stick-slip' as they move under load.

Another method that would give accurate diameter and sweep information would be to hold the log stationary and move the scanner lengthwise along it. This could use an Optimux or Rema type system on rails with a pulse encoder on its drive. The accuracy of this system should be very good, depending mainly on the alignment of the rail system instead of log transportation.

Using a video 'snapshot' system has the advantage that you don't need any transportation system to measure the log. This greatly simplifies the design of the conveyor system which now can be designed for log handling instead of compromizing to include a scanning system. The main additional expense here is that the scanning area has to be roofed over so that the lighting can be controlled. A successful video system which we have installed on a headrig in our mill is Applied Scanning Technology's video edge detector. It uses standard black and white television cameras every five feet to give front and back log edges every inch and a half using a special hardware edge detector. Other video systems using very high speed parallel processors developed for the robotics industry will someday become fast enough and powerful enough to do the job too.

Defect and Log Quality

The other thing we would like as an input is log quality and defects. Research is just beginning in earnest and the results may not be expected to be installed for a few years.

The other way to get this information into our computer is to provide the operator with some buttons to indicate what kind of wood he sees in the log. But let's not overload him with too many buttons to push.

The Optimizer

Once we've gathered all the information about a log that we need the first thing we would like to show the operator is the length of the log. The next thing we could do is show him what bucked log lengths he can get out of it using the length information only. This would give him an accurate idea of what log lengths he could get and how much overtrim or log leftover he would be left to play with.

If we have a complete diameter scan we can use this information to do some real optimization to try to improve our product value. This would allow us to determine what order to cut the lengths in.

So, how do we use diameter information in an optimizing program? The simplest thing to do would be to use diameter breakpoints to determine what size cants we could get from parts of the log. This is simple, fast, and can be re-done very quickly as the log is processed.

A big step up in complexity and profit potential is to use pre-calculated 'look-up tables' based on diameter and length generated by a program like SAWSIM ahead of time.

For the most complete solution, you could calculate a unique solution 'on-line' for each log as you get it using a lumber price table. This demands a very large amount of computer power unless you can include some shortcuts that give adequate results.

An important consideration with any optimizing system is the number of possible solutions increases dramatically with length. This really comes into play when you remember that the solution should be re-calculated any time that cutting deviates from the expected, i.e., for sweep reduction or for defect removal.

In case you think, "Well, you only cut up one log every minute or two, so you have lots of time for computing," I'd just like to mention the following.

From the time our cutoff saw starts cutting into a log until the front end reaches the 10 foot log stop is 7.5 seconds. If you subtract the time needed to lift the stop and halt the conveyor, it doesn't leave you with much time to decide what to cut and display it to the operator. And ours is a very slow conveyor system.

Here we have a decision to make in designing the system. Do we have enough information to justify a complete optimization, when we may be able to do it only once per log? Or do we do a less perfect solution and recalculate each time the operator overrides the decision? How often the operator has to deviate from the given solution determines how much we can automate the process.

Before you can calculate a reliable bucking solution you should have the sweep. What are the benefits of knowing the log's sweep? Well, you can improve the recovery by bucking the log into straighter sections. You can do better value calculations, and you will get fewer overrides from the operator so you can automate the process.

The considerations to take into account when bucking for sweep are the following:

- You must get a reliable, accurate measurement of the log's shape in the plane of its major sweep.
- The solution complexity is enormous as you must do an on-line calculation in real time. The variability of log shapes is too great for look-up tables to be reasonable. Therefore, the computer power needed becomes a real cost factor.
- If an override is made, do you re-calculate a new decision or not? If you don't have to redo it, you may have lots of time to do it right in the first place.
- It may be a good idea to give the operator a good grade input system and allow him the time to use it effectively by automating enough of the rest of the process.

Now what if we had a scanner that could also tell us everything about the inside of the log? In other words an internal defect detector. Well, now we're talking about absolute value maximization. We could see where the knots are, where the pocket rot is, and everything we need to know about where to go for clear and where to avoid. We could even pass the cutting instructions to the headrigs downstream with the log. Then the only need for scanners at these machines would be to aid in positioning.

The thing to consider for this system is that the measurements must be accurate, the scanner itself will be very complex and expensive, and the computer power required will be tremendous.

The Operator

So where does the operator fit into all of this. In the typical mill the operator is treated as a scanner, optimizer and control system rolled into one. This is true not only in log bucking, but everywhere in the sawmill. The operator is expected to see widths and thicknesses to a 16th of an inch at 20 feet, to know all the wane rules and grading rules for all the mill's products, and to be able to compare the value of all the different results he can get from pieces he can hardly wrestle through the machine fast enough to keep the foreman off his back.

On top of this he is given a verbal or written list of the product currently in demand and is expected to memorize them all for instant evaluation. As a result of this operator overload we can expect that the outturn does not always match the potential of the input material.

With computers, we can help the operator improve his outturn in several ways. We can measure sizes and distance to an accuracy he has no hope of matching. We can store sizes and grading rules in a perfect memory and recall them instantly. We can keep constantly updating cutting orders so we know what to cut at all times, and we can do value calculations of incredible complexity in a fraction of a second.

We can automate the system. This allows us to move everything at its maximum speed and coordinate actions so that several can take place at the same time. It also allows us to go directly to the final cutting position first time without having to jockey the setworks around.

When we relieve the operator of the things that computers do well, we allow him time to do the things that humans do well. One of these things is to recognize exceptions. If we remove the mundane, we allow the operator to focus on what to do with pieces with defects in them or pieces with high clear content. We can then ask him for an input to describe quality, or for an override to handle a piece with characteristics too complicated to describe to the computer. We can also ask him to handle more complicated machinery and do operations he would otherwise have no time to do, such as turn every piece at an edger.

APD Log Bucking System

At APD, we have two mirror image bucking systems, each with its own barker, scanning system, and cut-off saw. Both scanners are run from the same mini-computer. The hardware and most of the programming was supplied by Lloyd Controls.

The way we scan logs is we drop them into a conveyor with 43 pairs of photo-cells across it and a pulse encoder on the chain. The photo-cells reside behind slots in the sides of the conveyor. We also have an Optimux diameter scanner across the conveyor near the cut-off saw.

We found on our earlier installations at Somass, that there would be problems in length measurement caused by blocked photo-cells and logs slipping on the chains.

To overcome this, I came up with a way of tracking moving logs using only those photo-cells that changed state. When the front end of the log reaches our diameter scanner, we start taking lengths each time another photo-cell becomes blocked at the leading end or unblocked at the back end. When the front of the log reaches the cut-off saw, we calculate the average and the standard deviation of all the points. Then we throw out all the points that are more than one standard deviation away from the average, and average the remainder. This length is usually within 1/4 inch of the actual, which is the resolution of our pulse encoder.

At APD the diameter scanners are placed just in front of the cut-off saws, so there is no chance of using diameters in our optimization. We only use them for measuring the amount of wood consumed in our mill. Diameters are measured every 20th pulse of our encoder, so we get one diameter every five inches. Instead of relying on the pulse distance to give the length between scans for our volume calculation, we use the length scan length divided by the number of scans made to give us the distance between scans. This removes any error we would get from log slippage.

An advantage of using only length information is that each log would have only one 'best solution' for each log quality and cutting order file. Therefore, bucking solution tables are easy to calculate for each of these combinations, and the operator can choose from several different sets. Each time the operator makes any cuts, we re-calculate all the solutions, and the new solutions will appear as fast as the CRT updates.

The other thing we did was to automate the positioning of the log for leading end trim and kicking the processed logs into their appropriate destinations. Before we did this the usual practice was to lop about six inches off the leading end. Now we can stop the log with about one inch of it past the cut-off saw. This also allows the operator to take his mind off the logs once they are cut off, so he can devote more attention to the logs coming in.

One thing we sort of blew when we put this system in was the timing. The mill was operating for over six months before the computer was ready, and after it was installed it took another half year to get the control system running sensibly. During this time the operators got into a rhythm of running things manually, and this was very difficult to overcome.

Other APD Scanning Systems

One scanner is on our log quad headrig. It is a Kockums end-dogging system with controls supplied by Applied Theory. Its infeed consists of a very complicated scanner. The log is lifted up and clamped by a charger which then moves the log sideways through a light curtain. The plan view of the log is then measured at four inch intervals to a 100/th of an inch accuracy. We then fit as wide a cylinder as possible within the log outline, skewing it if necessary. We have some pattern look-up tables we calculated using SAWSIM, but for most of our logs we do a pattern on-line. It takes too much time to prepare SAWSIM and run off a big file, so when we need a new pattern it's easier to get the scanner computer to do the job for each log.

The operation of this machine is fully automatic. In fact we consider it to be our pet robot. It loads logs, looks at them, decides what to cut, hands them to the carriage, cuts them, and kicks the pieces off at the outfeed.

The operator just inputs what market the logs would be suitable for, rotates them for shake or sweep, and handles any screw-ups that occur.

Headrig

We also have a conventional headrig with carriage. It has a computer running the setworks, but this was used mainly as a positioner coordinator and backstand calculator. Then we added Leon Chasson's Video Edge Detector.

In the scanner installation at our APD mill, there is little hardware involved, especially compared to our log quad charger and light curtain. Each of six white tubes contains a standard RCA television camera looking down through a hole in the floor above the carriage loading area. Down at the loading area, we have special concentrated lighting to enhance the front of the logs on the carriage.

When a log is loaded on the carriage, the setting of the dogs tells the computer to fire the scanner, giving us a snapshot of the log. We then do a real time solution for the log, and when the 'set' button is pushed we go straight to the first calculated cut line. The time it takes the Sawyer from dogging the log to get its front end to the saw usually gives us enough time to scan, calculate and position the log at the first cut line. After the first face is finished, we bring the log back, drop it for the next face, and do another scan and calculation for this face too.

We have a lot of work left to do on this system to realize its full potential, but the benefits have been such that we run full time on scanner at the present time.

I will conclude by pointing out that this system struck hardest of all our systems at the pride of the sawyers. Their response has ranged from grudging acceptance to outright hostility depending on their perception of what we are trying to do. We are trying still to convince them that the scanner is just a tool for doing a better job, and not a replacement for their skills.

Video Edge Detection System

SCANNING, OPTIMIZED SAWING SOLUTIONS AND CONTROL FOR CONVENTIONAL OVERHEAD CARRIAGES, AND END-DOG AND SHARP CHAIN INFEEDS

L. Chaisson, Applied Scanning Technology, Mountain View, CA

The VED-200 multicamera scanning system acquires log diameter, shape, position and length data without log movement, and generates optimized sawing solutions for various forest industry primary breakdown machine centers. This new generation scanning and control system (see Figure 1) operates normally in severe sawmill environments.

The ability to scan and measure log size and position without log movement means less complex log handling machinery for new headrigs and straightforward retrofits of existing headrigs. With speed "snapshot" scanning, a high piece-count close-coupled small log mill may implement Best Opening Face sawing solutions using complete dimensional data. This "snapshot" capability also allows a sawyer to re-scan, after turning a log, with practically no additional lost time due to scanning.

Applications

Conventional carriages: two, three or four knees; maximum log length 16, 20, 24, or 28 feet; log diameters from 9 to 36 inches (6 to 60 inches as an option).

Overhead carriages: maximum log length 8, 12, or 16 feet; log diameters from 5 to 30 inches.

End-dog infeeds: maximum log length 8, 16, or 20 feet; log diameters from 5 to 30 inches.

Sharp chain infeeds: maximum log length 8, 16, 20, or 24 feet; log diameters from 5 to 30 inches.

Timing and Speed

The time required for VED to generate sawing solutions (commands to setworks) after a scan or re-scan signal is no more than the following:

Maximum log length (feet)	Time (seconds)
8	0.27
12	0.28
16	0.30
20	0.31
24	0.33
28	0.35

In a conventional carriage the scan signal is generated when the log is dogged. In a sharp chain infeed the scan signal is generated when the leading end of the log passes an optical limit switch at the log line. The scan signal may also be generated manually by the sawyer.

Location of Cameras and Scanning Method

In log scanning applications, the VED-200 has one inch Vidicon TV cameras mounted from 12 to 20 feet (depending upon the headrig and the building) above the bottom of the log. These cameras are along the log centerline and on four foot centers. For example, in a 20 foot carriage application there are five cameras above the carriage located 2, 6, 10, 14 and 18 feet from the log line.

Each camera takes diameter measurements of the log every two inches. This data from the cameras also determines the shape of the log (in the horizontal plane), the log location left or right of the saw line or centerline, and log length.

Lighting

The VED-200 is a front lighted scanning system. To provide the required contrast at the log edges, directed lighting is a part of the system and is located to the left and right of the sawline or centerline. Lights are configured in seven foot long banks. These banks are optimally located above the bottom of the log, between 12 and 16 feet, and to the right and left of the cameras, 12 to 16 feet.

Since our basic rule is to have the aim of the lights between 30 and 45 degrees from the horizontal, lighting for most headrig installations may be correctly configured to light the log and be in a protected location.

One of the key advantages to a front lighted system is that it does not become obscured by sawdust, chips or dirt. To ensure shock resistance and long life, AST used ruggedized low voltage lamps and then operated them at a lower voltage than specified.

Calibration

Fixed at about 40 inches below each camera, and in the field of view, is an array of 10 light emitting diodes (LEDs). Periodically VED-200 measures the location of these LEDs and compares the current location to the initial system inputs. If required, new calibration tables are automatically calculated and stored. This periodic calibration check is accomplished without operator assistance.

Accuracy of Measurements

The following overall system dimensional accuracies refer to headrig applications for log diameters from 5 to 30 inches and log lengths up to 28 feet.

diameter . . . . 0.1 inches standard deviation
length . . . . 1.0 inch standard deviation

Cubic scale measurement, in tests of 100 log samples, is accurate to three percent.

Diagnostics

Should there be a problem with VED-200, AST has developed over 20 diagnostic routines to assist maintenance personnel in quickly determining the cause of the problem at printed circuit board or camera level. Some of these routines run when the system is between main measurement and control functions (in the "background" as a programmer might call it).

Of additional assistance are power supply voltage indicators and LED displays for selected edge location, along with input and output status LEDs which indicate the state of peripherals.

At a higher level, the entire system may be analyzed by a process we have developed which functionally single-steps from acquisition of raw data on the first camera through generation of control signals.

Displays and Controls

Raw camera signals, system generated diagnostic displays, and alpha-numeric information along with production information may be selected for display on the system CRT monitor. Selection of this data is by a 28 position keypad on the system front panel.

Edge locations for a specific camera and scan line number are displayed on a front panel numerical LED display. Selection of camera and line number are by thumbwheel switches. In addition LEDs indicate "Data Valid", "Scan Mode" and "Operate".

Output Interfaces

Interfaces to most controllers of precision setworks are available. The serial interface to the report printer is RS-232. An RS-422 printer interface is optionally available should the printer be located some distance from the system.

Sawing Solution Program

Setworks commands are selected from a table of data stored in the system "application" microcomputer. The particular bandmill set and infeed offset commands are selected based on the log dimensions measured by the cameras, video preprocessor and "scan" microcomputer. The stored table is generated by AST and based on the Forest Service "Best Opening Face" program. Other sawing solution programs are optionally available.

Scale and Tally Reports

At the end of each shift a report is printed which lists total logs processed, gross cubic volume, average small end diameter, average length, average cubic volume and a tally of logs processed by small end diameter and length. After each report is printed the accumulated data is cleared. The report shows the time and date printed along with the time and date the last report was printed.

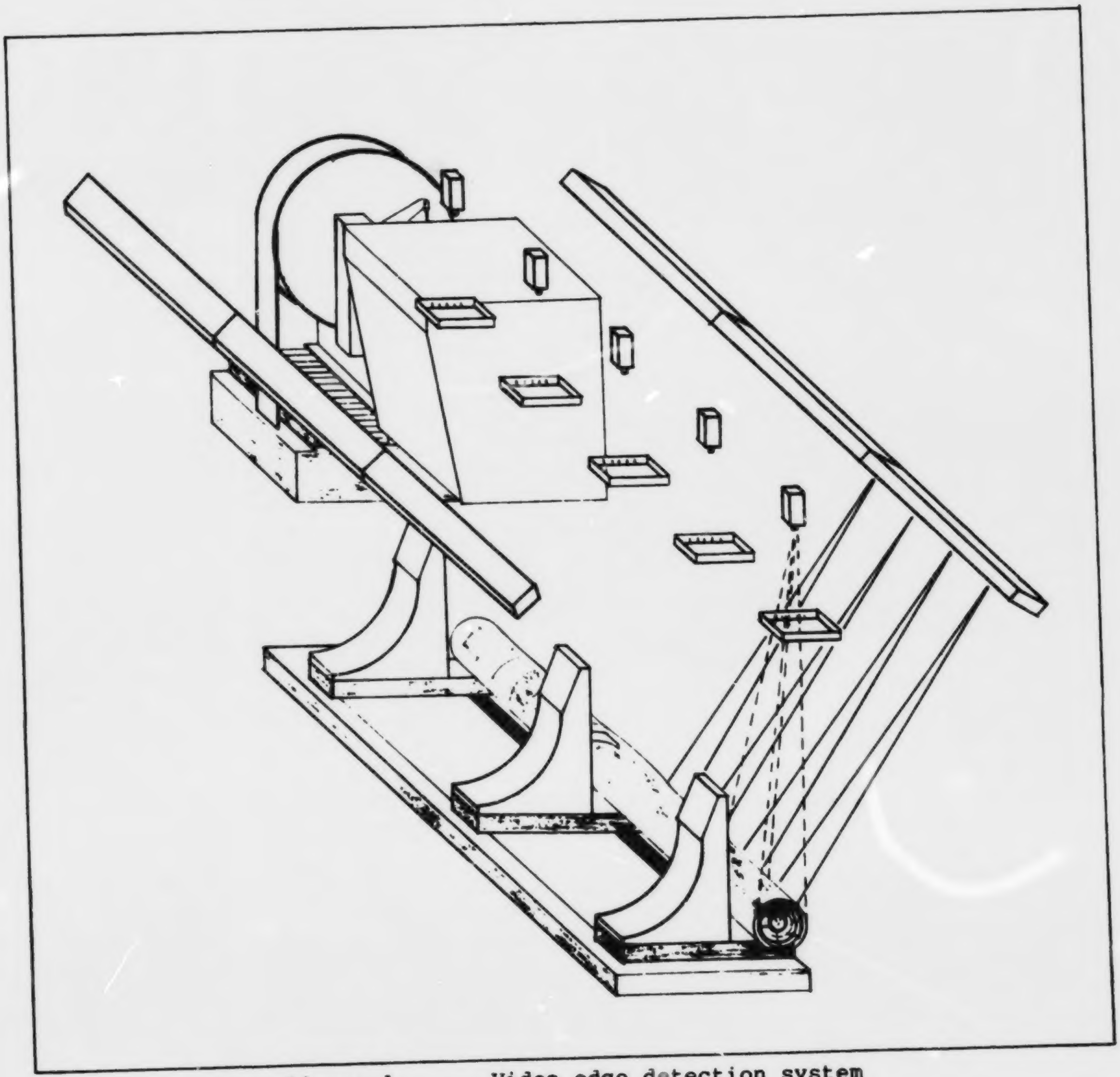

Figure 1. Video edge detection system

Ultrasonic Scanning in Wood Product Manufacturing

R. Bertram, Black Clawson, Inc.,* Everett, WA.

This topic concerns ultrasonics in scanning techniques for wood products. Black Clawson's use of ultrasonics is specifically with respect to range measurements and uses ultrasonics in an air environment rather than under water. It is not particularly suited to positional representation of an object in space. If you have an array of scanners you can determine the positional reference of an object and, therefore, determine the optimum position for a particular process.

I will review some ultrasonic principles. I will discuss the Black Clawson ultrasonic scanning system and how it is used in the wood products industry and then examine some Black Clawson applications, things we have functioning in the industry right now, as well as some things we have tried that have not been particularly successful.

In his 1979 report, Dr. Szymani defined ultrasonics as the generation, propagation, detection and evaluation of sound waves at frequencies greater than the normal hearing range (which is about 20 kH). The nondestructive evaluation of sub-surface defects is one of the uses that has been proposed for ultrasonics. However, in practice, no one has successfully produced a system that will recognize defects in lumber. The underwater technique is a difficult technique from the standpoint of producing a machine that will do the job.

The use of ultrasonics in air for defect recognition is not particularly suitable, due to the extremely high power that would be required in order to transmit a pulse that could penetrate through a particular material. One of those problems, which will be discussed shortly, is acoustical coupling.

Distance measurement (the standard sonar type of technique used in submarines for detecting how far away an object is) is the primary use of ultrasonics at Black Clawson. For range measurement, a sound wave is simply pulsed out and the time duration measured for the wave to traverse to an object, strike it and then return. This is quite a reliable and accurate method since the properties in air are overcome.

Figure 1 is a simple block diagram showing a typical ultrasonic system. On the right side is the transducer with a breakdown of what transducers are supposed to do and how they can be used for distance measurement. Basically, the transducer is a device which allows us to convert from mechanical to electrical energy and vice versa. When the transducer is struck with an electronic impulse it causes a mechanical stress to appear on the Piezo electric material.

This transmits a mechanical wave which traverses the medium, strikes the object and returns. On its return, the mechanical wave front stresses the

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*Now Acrowood.

Piezo electric material again, creating a receive impulse. A pre-amplifier is used to detect the impulse using receiver circuitry. Timing and control of the system is necessary to synchronize the operation for the computer system which can then utilize the data to make a decision as to how the ultrasonic pulse represents the real world.

With respect to the transducer (Figure 2), and keeping in mind the system is for use in air, one of the problems in utilizing ultrasonics in an air medium is the acoustic coupling between the ultrasonic device, the Piezo electric ceramic element, and the air media. There is no known easy way to do this. Really high efficiency cannot be achieved, in terms of power transmission from the element to the environment, when transmission is in air. The solution to the problem of how to cross the acoustical barrier is through the use of power.

Therefore, the element that Black Clawson uses in their ultrasonic scanning system is typically a high powered transmitter-receiver combination. Transmission uses much more than 1 watt/cm^2 on the element itself, which is quite a bit of power. It turns out that in normal application 300 watts are put into the transducer element on transmit. This scanner is very well suited to application in an industrial environment. It is a kynar encapsulated device which is impervious to 300 or more chemicals.

In five years there has not been one scanner failure in terms of the transducer itself and no physical deformations in terms of chemicals eating away at the encapsulating material. Therefore, the transducer is quite suitable for use in a mill environment. It can be put almost anywhere as it is impervious to oil, etc.

Since this is a ranging device it is desireable to have a point measurement system. Of course, when a wave is transmitted a point measurement system is not possible as it spreads out to some degree. However, through the use of various mechanical techniques in the design of the transducer a very narrow beam can be produced.

The type of beam that is used in Black Clawson's transducer has a seven degree included beam in the main lobe with the side lobes being low enough not to be important in the measurement of the system. A very directional signal comes from the transducer and returns. With a seven degree cone there is the advantage of being able to move the transducer a little bit further away from the device or the material that is being measured while maintaining a fairly accurate point measurement system. This is desirable for this type of application because the physical movement of material through the scanner ray is quite difficult.

The Black Clawson transducers use a longitudinal wave generation technique with a metallic band circulating the ceramic element to keep the side lobes to a minimum, so there is a high directivity toward the seven degree cone previously mentioned.

On the back end of the transducer there is a preamplifier. One of the problems with recognizing a returned ultrasonic signal is the relatively low amplitude of the signal. Because of the dissipation of sound through air, which follows the inverse square law, the signal which is returned to the transducer element is fairly small. The signal must be recovered from the ambient noise that exists.

Black Clawson incorporates preamplifier circuitry at the transducer located out in the process environment. For process control the preamplifier is placed close to the transducer so that the electrical noise which is introduced into the system can be minimized.

A disadvantage of this arrangement is that some method of passing the transmission poles is required. These are the high powered, high voltage transmisson poles from the transmitter circuitry to the element. The signal, which is quite high in amplitude, cannot be put through the preamplifier, so another way of by-passing it must be found.

This means there is a significant amount of power absorbed in the preamplifier by-pass circuits, therefore, the actual transmission power generated by the transmitter circuitry is significantly higher than the amount of power needed to excite the transducer, in the order of two to one. Twice the amount of power must therefore be transmitted through the co-axial cable to the transducer than gets to the transducer and is converted to actual mechanical energy. However, since this power is over very a short duration, it is not a particular problem from an overall system power standpoint.

The primary advantage of the preamplifier circuitry is to allow the computer circuitry and the power generation circuitry to be some distance away from the actual transducers. The computer system has been located as far as 200 ft. away from the scanning device with no apparent degredation in the signal-to-noise situation.

The transmitter circuitry, which is part of the block diagram in Figure 3, gathers the pulse burst which is required to excite the transducer. It also provides for a receiver dead-band hold-off. With any piezo ceramic element which provides both the transmit and receive function there is a certain amount of time, during the transmission and very shortly thereafter, where it is not acceptable to receive signals.

Furthermore, beyond being unacceptable, it is desireable for the receiver circuitry to be disabled during this time so that there are no erroneous trigger pulses which do not relate to the object being measured.

A third function is to provide the high power or power amplification cutput drive to the transducer. The method used here produces a 1600-volt peak-to-peak pulse which provides in excess of 600 watts through the co-ax cable. Also, adjustment for an optical match to the transducer environment must be provided. The actual resonant frequency of the transducer and the matching of impedance throughout the whole circuitry must be provided in order to have optimum power transfer.

On the left hand side of the block diagram (Figure 3), there is a transmit command which is generated by the timing and control function of the overall system. The transmit command performs two functions. First, it activates the receiver dead-band hold-off generator providing two functions:

- It goes out and enables the transmit pulse. The transmit pulse cannot be enabled to proceed through the circuitry unless the dead-band hold-off has been achieved, otherwise the receiver circuits may be damaged.

- It fires the transmitter control circuit which actually controls the generation of the transmit burst. The wave forms at this point are simply a series of pulses which are generated and gated by the dead-band hold-off circuit. The output of this gauge then generates a pulse train into the power amplifier. The power amplifier, which is impedence matched to the transducer circuitry, will provide the high power transmit pulse. The output of the power amplifier is quite significant with a feed voltage of 1,600 volts, which generates quite a large bang on the ceramic element giving a large amount of transmit power. The little clicks that are created by this pulse banging away on the ceramic element can be heard in close proximity to the scanner array.

The receiver section of the scanning sytem is probably the trickiest part of the system to design because a relatively low signal level is returned from the transducer. Also, in a mill environment there is a relatively high level of ultrasonic energy in the air due to the amount of compressed air used and the peeling noise from the veneer knife. It is somewhat difficult to distinguish the return signal from the ambient noise and this is necessary in order to make accurate measurements.

Therefore, one of the functions of the receiver is to at least detect the return signal. The block diagram (Figure 4) shows some receiver tuned circuitry which matches the transducer for optimum band pass characteristics. The center frequency is band passed so that the outside noise of the band of particular interest is rejected. A unique signal correlation circuit is used for correlating the receive signal based on the transmitted signal.

This is the device or the circuitry on the receiver board which allows maintainance of a high degree of repeatability with the signal. The receive signal can be pulled out of the ambient noise with a very high degree of success using the signal correlation circuitry designed into the card. In addition, and in conjunction with the signal correlation circuitry, there is a dynamic gain control called an instantaneous gain control which overcomes the following field problem.

The problem is a result of transmitting more than one burst of energy. The burst of energy actually consists of about eight or nine pulses which are transmitted out to the object and then received back. The relative amplitude of the lobes changes depending upon the environment--whether or not it is going through a temperature gradient, what kind of object it strikes, and so on. The distance from one lobe of the wave front to the next lobe represents a relatively significant difference, in terms of measurement accuracy. It is, therefore, desireable to be able to trigger one of the lobes consistently. If, for example, on the first transmit a particular wave front is detected and, for some particular reason, on the second transmit of multiple transmissions a different wave front is detected there could be as much as a quarter of an inch error in accuracy, depending upon such factors as the distance of the transducer from the object. This degree of accuracy is unacceptable. Therefore, it is necessary to trigger a particular lobe all the time. There are two methods in the circuitry that allow this. First, the signal correlation circuitry detects the proper signal. An instantaneous gain control is generated from the receive signal allowing the demodulation circuitry to give a demodulation output and a signal from the IGC. The output and signal, when properly adjusted, lie in the band which relates to the specific wave front required. Over the distances used the system can be adjusted to give about 97 percent accuracy in detecting a particular wave front. This has eliminated one of the basic problems of the original design.

The Black Clawson veneer block optimizer (Figure 5) is one application of ultrasonic range measurement. For veneer block optimization, a veneer block is scanned prior to being chucked in a veneer lathe and its spatial orientation determined using the ultrasonic scanning system. Using a computer real time solution, the block is positioned on its optimum axis and placed in the lathe for peeling. This provides for a maximum yield for each veneer block in real time. Successes are being achieved that range from a 4 to 10 percent improvement in mills, depending upon the basic raw material.

The Black Clawson in-lathe block-scaling system overcomes a problem that has long plagued mill management and that is: How much wood actually goes into the lathe system as compared to how much wood is on the tray system, so that the efficiency of peeling can be determined. Ultrasonics are being used in this environment to scan the block as it enters the lathe, as well as during peeling, making it possible to determine exactly what happened with each of the blocks and to provide a management report.

The ultrasonic system has also been used in a green end lumber trimmer reporting system. The nominal thickness of boards is measured as they go into the trimmer system. The saws that are dropped by the operator are also recorded and an end-of-shift tally is created showing all of the boards that went into the system and the type of lumber produced from them. Ultrasonics have been used in other environments, some of which are still being worked on and some of which have been abandoned.

A very good use for ultrasonics in a veneer mill is to control the tray speeds in order to keep the veneer flat on the tray. One of the problems with veneer as it comes out of the lathe and goes into the tray system is the bubble or buckling effect due to the difference in speed of the tray systems. Ultrasonics are fast enough to detect a rise in the veneer and control the speed of the tray system to compensate. This stops some of the tearing of the veneer that results from this phenomenon.

In the past, optical scanning has been used for veneer defect recognition at the clipper in the Black Clawson clipper control system. Basically an overhead light source is used with an under broken table type of photodiode technique for through-the-wood defect analysis. There are certain problems with this type of system, e.g., detecting defects such as splits in the wood if they are not pulled apart. This is a definite problem that has not been overcome other than to have the operator stop the wood on one end of the split and then when it opens up it can be detected.

Edge detection of defects in the wood is another problem because registration of the wood on the table is not linear. It moves back and forth so there must be higher scanning resolution at the edges of the sheet.

Another optical technique that has been used at Black Clawson is the light curtain for diameter measurement for small log optimization. For the small log optimizer the blocks are passed through a light curtain arrangement, with discrete cells for measurement of diameter every six inches along the log, using the computer for real time solutions. Thus, the best sawing pattern is generated for the block and the saws and block are adjusted accordingly for sawing into green lumber.

Black Clawson has attempted to use lasers for scanning. The green end trimmer reporting system referred to here is actually a fall-out of a system currently being developed which uses a laser camera combination to scan green wood going into the trimmer, analyze the wane and cut the wood accordingly. Some of the problems have been solved but not all of them.

The biggest problem in using lasers is that the environment is two-fold. First, it is sensitive to the ambient conditions, and second the operator wants the wood to be close to the saws so that he can make adjustments before the wood gets into the system. The affect of ambient conditions on laser use is severe enough to warrant blacking out the environment so that the wood can be seen all the time. However, operators do not like working in the dark so this particular technique is not viable. The second problem is the expense of laser systems. In order to get the resolution needed to do the job, a lot of lasers and cameras are required and the cost of the system becomes prohibitive. These are some of the problems encountered, they have not all been solved but they are still being worked on.

Question Period

Question

I understand that an ultrasonic system used in the outboard industry for a number of years utilizes air coupling. Does it use the same technique as you to increase the transmission?

Answer

I can only make an assumption in answering that question because I am not familiar with the system you are referring to. However, in my experience with transducers in air I see no other method by which they could overcome the acoustic impedance problem between the element and air. There is such a tremendous difference between the acoustic impedance of air and the piezo electric material that there is no way to overcome it, other than by using high power.

Question

Since your whole design is based on trying to have the transducer some distance away from the object you are measuring, do you need to dampen out the chemical energy that you are generating in the transducer?

Answer

Yes, that is the dead-band hold-off that I was referring to.

Question

Do you physically go in, do you try to dampen it out using something, or do you just let the transducer take care of itself?

Answer

The transducer takes care of itself. The design of the transducer is such that you minimize the amount of vibration that occurs after your pulse. Specifically, they take the ceramic element and put a metal band around it and the metal band stops the radial expansion. The longitudinal expansion appears to dampen away very quickly due to the absorption material behind the element and, if you can stop the radial expansion, the dampening effect happens very quickly. Obviously, since you are using the same element to receive as you are to transmit, there are limits to how much you can dampen the element and still be able to recognize the receive pulse. There is always a trade off between these two properties.

Question

Do you find that two element transducers, one for receiving and one for transmitting, improve your efficiency and eliminate the dead-band?

Answer

We have done that, but there is a problem with the spatial arrangement of the transducers and aligning them so that the tansmit pulse hits the reflective material (whatever you are trying to measure) and comes back to the receiver. You have a certain amount of angle of incidence and handling that in a mill environment, while the wood is passing transversely through the scanner, is not a very simple matter mechanically. It turns out that, with the design of our circuitry and the elimination of some of the problems that are associated with the use of transducers in air, two element transducers are not necessary. We will talk a little bit about the accuracy of the system and you will find when I quote some of the accuracy figures that we can do quite a good job in this range by measuring with a single device. There is also the cost of producing a system, if you use one transducer to transmit and another to receive you simply double the cost of the transducer arrangement and, of course, the main idea in manufacturing a process control system is to keep the cost down.

Question

At approximately what frequency do you operate?

Answer:
We are operating in the 20 to 100 kH range.

Question

How do you handle temperature problems?

Answer

In all of our applications we have a digital thermometer system, strategically placed in the scanner ray, to monitor the temperature of the environment and the computer adjusts the measurements that it takes compensating for the actual temperature of the environment. The exception is the green end trimmer because we are in a position to be shooting the ultrasonics at a reference, the table on which the trimmer lumber is running. We can provide dynamic temperature compensation, based on the known distance from the transducer to the table, and that temperature compensation is performed for each piece of lumber.

Question

What sort of pulse referencing frequency do you use?

Answer

The repetition frequency. (Actually the repetition is quite low.) We don't have a real high duty cycle because of the temperature problems with the transducer. If you bang away at the ceramic element too often you will cause it to heat up. Repeated heating will eventually it to the cure point where it will destroy itself. However, that's not the case here. The transducers are probably fired about once every 15 milliseconds, which is quite a lengthy time in terms of frequency.

Question

What is the cost of the ultrasonic system?

Answer

The cost, for actual materials, of a single channel of ultrasonics is probably in the order of $1,200. Obviously this figure does not include the computer end which drives it. The cost of the hardware components, to get from the computer out to the real world and back, is of the order of $1,200.

Question

How does it compare with the laser system for log optimizing?

Answer

In terms of costs its quite a bit cheaper than lasers. Reliability wise, I don't have any statistics on the lasers. The ultrasonic system is extremely reliable, in five years of use in the field we have never had a transducer fail. The circuitry is all of the latest large scale integration type. There is no circuitry that is unique in terms of its reliability factors, it is made up of off-the-shelf components with one or two exceptions and therefore the mean time between failures is quite long. I have personal experience in the use of the veneer block optimizer and have seen at least two systems operate for three years without any failures in the ultrasonic system. Of course, one of the problems with the ultrasonic system which has just been overcome is the installation and adjustment. It is somewhat difficult to adjust since it requires oscilloscopes etc., to achieve the optimal adjustment and it is not usual for mill maintenance people to use this kind of equipment. There are two things we are doing in this area. Number one, we are offering training to technicians working in the mills to bring them up to the high level of technology required for these types of adjustments. Also, we are redesigning the circuit to eliminate the need for that particular operation and we have a new circuit board coming out which will eliminate all those adjustments. It is all done by the machine.

Question

How close together can you put the transducers in the trimmer application?

Answer

They are spaced 18 inches apart on the trimmer and are 24 inches from the surface of the table.

Question

How close should they be?

Answer

I think that is probably as close as you could get then with this particular arrangement due to the seven degree cone and reflectivity from one transducer to the next. Cross-talk interference is a problem at that point.

Question

You said you were going to mention something about procedures and accuracies.

Answer

On the green end trimmer table, because it is an environment where we are shooting straight down at the table, we have achieved repeatable accuracies of 0.030 in. with this system, which for measurement of nominal sizes certainly is sufficient. On the veneer block optimizer, an in-line scaling system, we are achieving repeatable accuracy of the order of 0.070 in. which from the standpoint of positioning a roughly debarked log into its optimum position is certainly accurate enough.

Question

How far can a transducer be from the material to be measured?

Answer

We have used the transducer as close to the material as 18 inches and as far away as 6 1/2 feet. One of the problems, of course, in considering the distance of the transducer from the object is the scan time. It takes a finite amount of time to get from the transducer to the material and back and as you increase that distance you increase the amount of time you need to scan the device. One scan is not enough, you must fire the transducer multiple times and then statistically average the return signals in order to produce a correct result. So, obviously, the idea is to get as close as possible to reduce the scan time but there are certain physical limitations due to the fact that you must process the material through the scan tray.

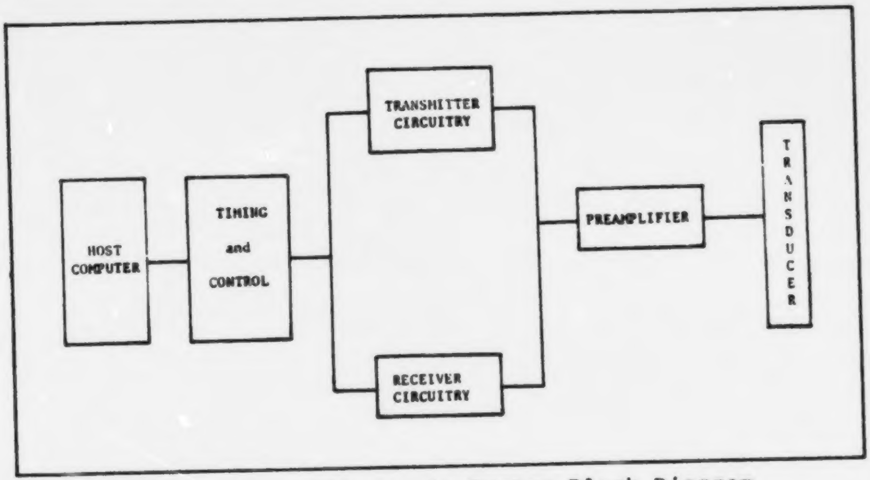
TRANSMITTER CIRCUITRY
HOST COMPUTER
TIMING and CONTROL
PREAMPLIFIER
TRANSDUCER
RECEIVER CIRCUITRY

Figure 1. Ultrasonic System Block Diagram

High power piezoceramic element

Kynar encapsulated for use in industry

Seven degree included angle cone beam pattern

Designed for use in air

Figure 2. Ultrasonic Transducers

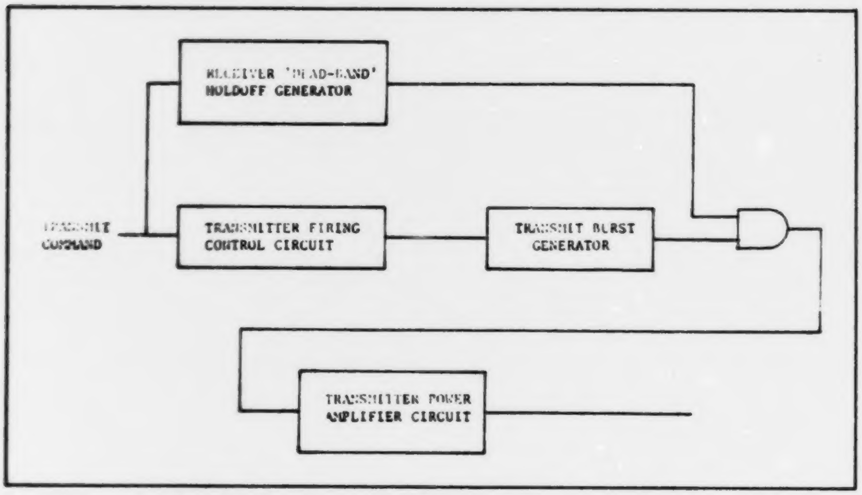
RECEIVER 'DEAD-BAND' HOLDOFF GENERATOR
TRANSMIT COMMAND
TRANSMITTER FIRING CONTROL CIRCUIT
TRANSMIT BURST GENERATOR
TRANSMITTER POWER AMPLIFIER CIRCUIT

Figure 3. Transducer Block Diagram

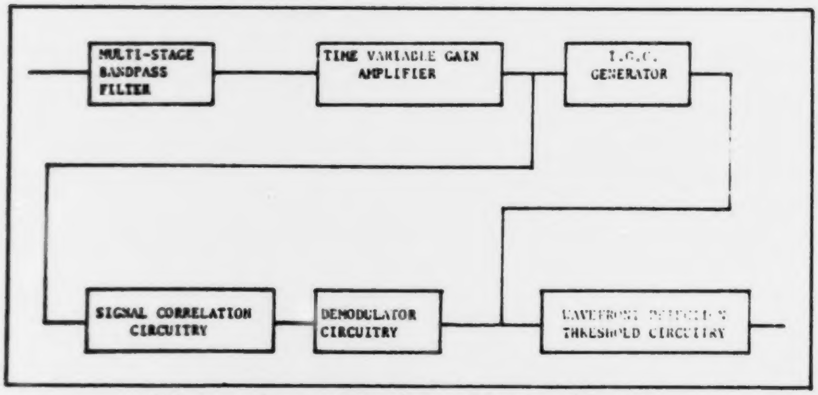
MULTI-STAGE BANDPASS FILTER
TIME VARIABLE GAIN AMPLIFIER
T.G.C. GENERATOR
SIGNAL CORRELATION CIRCUITRY
DEMODULATOR CIRCUITRY
WAVEFRONT DETECTION THRESHOLD CIRCUITRY

Figure 4. Receiver Block Diagram

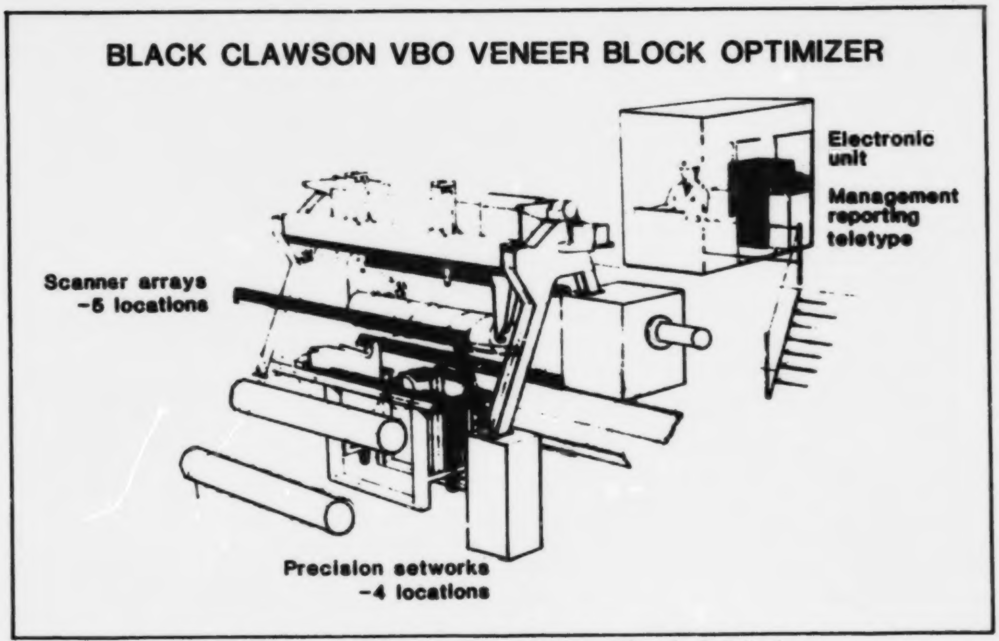
BLACK CLAWSON VBO VENEER BLOCK OPTIMIZER
Electronic unit
Management reporting teletype
Scanner arrays -5 locations
Precision setworks -4 locations

Figure 5. Ultrasonic Veneer Block Optimizer

Electrical Scanning in Wood Application to Moisture Content Gauging

R.S. Parker, Weyerhaeuser Company, Tacoma, WA

In most cases where process control or continuous monitoring is desired in a manufacturing facility the use of 'direct' measurements is not possible. By 'direct' measurements I mean a measurement which closely resembles the fundamental definition of the property under consideration. An example might be a measurement of the material's density by sequential evaluation of the sample volume and the sample mass. Such a means of finding lumber density would be considered unecessarily cumbersome and, to my knowledge, is seldom done.

The use of electrical techniques to provide process control, or to monitor properties of interest to manufacturing personnel, exploits what might be called 'indirect' measurements. For example, the use of dielectric observations to infer the moisture content (MC) of wood exploits the previously developed correlation between the dielectric constant or dielectric loss of wood and the sample MC. The use of a gamma densitometer exploits the known interactions of gamma rays with atomic matter.

When using such 'indirect' scanning technologies it is always necessary to understand the phenomenon which is to be exploited in the measurement. In some cases the accuracy of the measurement is limited by this correlation, while in others the technology itself, or its implementation, will provide the accuracy limits. A thorough knowledge of the physics at work will allow an intelligent assessment of the chances for improvement and where such improvement is like to be possible.

Electrical scanning has long been an appealing option for these 'indirect' measurement options. It can frequently be implemented in a 'non-contact' mode and, for all but the lowest frequencies, has the speed to make instantaneous readings on-line for process control. Finally, electrical properties of wood materials have been well correlated to several wood parameters which are vitally important for process control. Particular examples are MC, density and grain direction. Each of these can be inferred from electrical scanning with some degree of success. Though these methods can be used to evaluate other parameters than MC I will focus on MC gauging in this paper.

There is also one particular problem which I would like to discuss. In this industry, for the purposes of convenience, it is normal to hear people talk of **the** MC of a given board when, in fact, the MC of a piece of lumber is a continuous function of position in the piece of wood. Now if one is building a house, the presence of wet spots in a 2 x 4 is of no great consequence. However, if one is gluing up an expensive lam-beam, the presence of even small wet pockets can be a disasterous mistake.

Figure 1 is a plot of the MC vs. position along the length of a production hemlock 2 x 4 from one of our NW mills. This particular piece exhibits quite wild behavior. Pieces like this are representative of perhaps 10 percent of all production hemlock material. To label a sample like this with a single MC value is misleading at best and dangerous at worst. Good lumber MC meters must be able to detect such MC variation and respond appropriately according to the intended purpose of the product being produced.

Figure 2 shows a schematic representation of the frequency range of various electrical spectroscopies, and the general physical mechanism which absorbs the electrical energy and thus allows inference of the desired information. These technologies will be broken into DC-audio, radio frequency, microwave and infrared/optical spectroscopies. Each of these regions will be separately discussed with attention paid to strengths, weaknesses, and at leat one particular example of currently available commercial equipment.

DC and Audio Range

These measurements observe the motions of ions as they migrate through the wood material, and Table 1 shows some properties of this regime. Below fiber saturation wood behaves as a semi-conductor and evaluation of the wood resistance can be used to infer wood MC with some accuracy. Unfortunately, the MC in wood during mill processing varies greatly throughout the volume and these resistance measurements suffer greatly from statistical insufficiency.

Audio frequency measurements are generally better than DC measurements since they usually are obtained in such as way as to average their reading over a fairly large volume of the sample and thus have greater security from this local variation of MC through the wood. Both DC and audio measurements suffer from the presence of grain-related anisotropy of the effects and care must be taken to either correct for grain defects or measure in such a way as to be able to justify ignoring such effects. Since these methods are exploiting the semi-conducting nature of wood, temperature effects are important and must be taken into account.

Figure 3 shows a plot of the resistance of a wood sample vs. MC and temperature. Note the large variation of resistance vs. both MC and temperature. Above fiber saturation the semiconducting nature of wood weakens and these low frequency techniques become substantially less successful. Though some vendors market gauges based on low frequency or DC conductivity for green material their accuracy is severely reduced where MC is in excess of 30 percent.

DC conductivity measurements are used to infer MC for lumber in the ubiquitous Delmhorst manual, lumber moisture meters. This meter is currently the most accepted standard in the industry for measurement of production lumber, both in hot checks in the kiln and for dry-end quality control. Accuracy of this meter is in the three to four percent range.

There are several different manufacturers selling gauges which use AC conductivity for on-line MC gauging and detection. These include Mann-Russell and Lignomat. These gauges require sample contact and must be carefully compensated for material temperature. This technique is not sensitive to sample density.

Low frequency AC methods are currently being used in a new gauge being marketed by Strandberg Engineering Labs of Greensboro, NC. This meter (Figure

4) uses up to four sensing heads to evaluate the MC along the length of a board as it passes on a transverse conveyor. Since the sensor averages over a length of 30 - 40 cm it is less subject to errors related to small moisture pockets than the meters discussed before. This is also the first gauge to be discussed here which has a memory to collect this data and allow later evaluation of load MC and even reconstruction of the MC profiles within the kilns (see Table 2).

Radio Frequency

These methods observe the dielectric loss and dielectric constant of wood at frequencies of several hundred kHz to 50 MHz (Table 3). These gauges are used both for low MC measurements, and for green wood. Though these properties can be successfully correlated to MC, they are strongly dependent upon sample mass (density and volume) and must independently be corrected for the total observed sample mass.

These gauges again must be designed to ignore or compensate for grain direction. Temperature effects in this frequency are much smaller than at lower frequencies but must still be taken into account. Such gauges (Wagner) are currently the most plentiful in lumber mills in the US.

Microwave

The use of microwaves for MC, density and grain angle determination is only now becoming really feasible. It remains an attractive but elusive goal (Table 4). The several microwave technologies allow rapid inference of these parameters over a small volume (determined by the wavelength at the chosen frequency) which can be repeated and averaged over the entire volume of the sample board. There have been several attempts to market such gauges to the wood products industry over the years with, at best, limited success.

Recently, a Finnish company has marketed the 'Finnomoist' gauge (Figure 5), which seems to work quite well but has not been fully licensed in the US because of the presence of a gamma ray density sensor. There are simpler microwave gauges on the market but they appear unsuitable for use in lumber applications.

The Finnomoist gauge has been marketed in Europe with some success and, in fact, demonstrates the best ability yet to predict the oven-dried MC of lumber. It is currently only configured to be used in a longitudinal-feed location in the mill and requires some contact wih the board (for the length encoder). They operate by measuring the power lost by a microwave beam during transit through the board and use this, along with the results of a gamma density measurement, to compute the MC. These values are computed every 1 or 10 cm along the board from which the average is computed for control use. The computer is also able to store these average data and produce a printout of load histograms for management evaluation (Table 5).

Infrared Reflectance Spectroscopy

This is a relatively recent addition to the arsenal of technologies for the indirect measurement of MC. In these gauges the sample material is subjected to irradiation by a near infrared light, and the reflected light is collected and analyzed. The particular light frequencies which are strongly absorbed by water are selected and their amplitude measured. By comparing the intensity emmitted from the light source to that reflected from the material surface, an accurate MC can be obtained.

Table 6 shows a compilation of the properties of these gauges. They are particularly insensitive to temperature, grain orientation, and species effects. The bad news, however, is that IR radiation is not able to penetrate any deeper than a fraction of a millimetre into wood. This means that if your lumber is dryer on the surface than in the center of the piece (a virtual certainty), the gauge will yield a drier MC than is appropriate. In general, these gauges are inappropriate for use in lumber MC evaluation. They are, however, particularly valuable for paper, chips, and composite board applications.

Strandberg Engineering Labs Moisture Monitor

This constitutes the end of the general introduction to technologies being used at this time for the direct evaluation of lumber MC's. I would like to return to a discussion of the Strandberg MC gauge which we have installed in several of our mills. This gauge is a non-contact gauge which senses the lumber MC by measuring the dielectric loss in the lumber as it passes over the sensing heads (Figure 4).

The passing lumber crosses an optical beam to announce its arrival and trips limit switches to signal its length. The instrument evaluates the dielectric loss at each head, measures the air temperature and then calculates a temperature corrected MC which is assigned to that board. The computer is capable of averaging linearly, or using a variety of complex schemes to weigh wet spots and control drop-out. A non-linear averaging scheme has been found especially valuable in hemlock drying owing to the large problem found with large persistent wet pockets.

The front panel layout of this gauge has been designed to allow mill personnel easy access to the information with minimal training. We have found in our mills that the unstacker operator can be trained to operate the instrument in a couple of hours. The panel functions have been broken into four functional groups including readout, species selection, output/printer functions, and data entry-error control-command input. The front panel is completely sealed with a Lexan overlay to prevent dirt, dust or water from contaminating the control electronics. The system is designed to operate from mill electricity using only about 90 watts of power.

Figure 6 shows a plot of the MC indicated by a gauge which has been modified to allow longitudinal passage of the sample lumber. It accurately indicates the MC of the board as it passes the sensing head. This data was obtained near the output of a planer at a line speed of nearly 6 m/sec. Though the computer is not able to send all these readings out in the normal separation between boards, it is capable of averaging them, and making drop-out decisions using this and other more complicated criteria. This decision can be combined with information from other machines (either within the gauge or in an external computer) to yield composition, grade or usage decisions.

The accuracy of the instrument has been obtained by doing extensive testing of production lumber at several of our mills. Figure 7 shows a plot of the standard deviation of the MC from this meter vs. the number of measurements made along the length of the board. Also included for comparison is the same information for the Delmhorst meter. Our tests indicate that when compared to the average MC of a whole 2 x 4 board, the Strandberg meter (with three heads in a transverse mode) is equivalent to seven 'sticks' of a Delmhorst meter. Now nobody stands on the line and sticks every passing board with their trusty Delmhorst, yet this meter does evaluate each piece. This is particularly useful in species where there are likely to be major problems with wets like hemlock and S-P-F.

Table 1

DC-Audio method characteristics table

Dielectric and conductance spectroscopy
(DC - 10kHz)

A -- Systems measure gross motion of free ions

B -- Generally require large pieces of material

C -- Highly sensitive for MC from 6 to 30 percent

D -- Highly sensitive to temperature effects

System examples

Lumber unstacker meter
Dry veneer detectors

Table 2

Strandberg printout

```
       STRANDBERG MOISTURE MONITOR MODEL M-620 REPORT
                        8/23/84  12:43

                            KILN #1

 CHARGE 26
 SPECIES 5 (2X12)
 MC CLASS    PCS    % PCS     % PCS *= 2%

  <6         409     14.4     *******
   6         238      8.4     ****
   7         385     13.6     *******
   8         417     14.7     *******
   9         296     10.4     *****
  10         243      8.6     ****
  11         171      6.0     ***
  12         109      3.8     **
  13          87      3.1     **
  14          73      2.6     *
  15          54      1.9     *
  16          50      1.6     *
  17          44      1.6     *
  18          56      2.0     *
  19          65      2.3     *
  20          51      1.8     *
  21          52      1.8     *
  22          32      1.1     *
  22           1       .0


 TOTAL NUMBER OF BOARDS       2633
 MEAN                          5.5%
 STANDARD DEVIATION            4.5%
 MEAN OF PASSED BOARDS        10.3%
 REJECTED < 7                 22.8%
 REJECTED >19                  4.8%


  CAR NO.  BOARDS     AVG. MC
                                               HOT METER - 16.27%
     1       495        8.8%                   CORRECTED - 13.27% @160F
     2       451        8.6%                               10.27% @200F
     3       514        9.7%
     4       496        9.8%
     5       368        9.6%
     6       509       10.3%
     7
     8
     9
    10
```

Table 3

Radio frequency method characteristics table

Medium frequency spectroscopy
(100 kHz - 50 MHz)

A -- Systems observe energy lost in polarizing molecules

B -- Response has grain orientation dependence, must be compensated

C -- Medium sensitivity to temperature

D -- Field penetration of sample generally slight (determined by classical 'skin depth')

E -- High sensitivity to sample density/mass

System examples

Lumber unstacker meter
Composites panel moisture gauges
Chip moisture detectors

Table 4

Microwave method property list

Microwave energy absorption or reflection
(1 GHz - 50 GHz)

A -- System observes the non-polarizing rotation of water molecules in wood

B -- Gauges are highly sensitive to grain direction

C -- Sensitivity range can be extended from essentially OD to green MC. Most useful for 0 30% MC

D -- Gauge response only weakly dependent upon product

E -- Systems can be constructed in both the transmission and reflection modes. Transmission mode preferred

F -- High sensitivity to material density/mass

System examples

Finnomoist (lumber)
Omega Controls gauge (composites)
Strandberg Labs (fabrics)
Scanpro (paper)

Table 5

Finnomoist data printout

```
*****   FINNOMOIST   *****

  MOISTURE   ( % )   AVERAGE   STATISTICS :

1.8.1980 14.59 1 56321789 345 45MM 175MM

TOTAL COUNT =   345,  LENGTH =   1725M, VOLUME  13.58M3

MOISTURE AVERAGE OF PASSED BOARDS = 13.9%

CLASS  PCS    %PCS   RM    %PCS *=2%
  <9     0     0.0 000   I
   8     0     0.0 000   I
  10     2     0.6 010   I
  12    18     5.2 090   I***
  14   103    29.9 515   I***************
  16   164    47.5 820   I************************
  18    51    14.8 255   I*******
  20     4     1.2 020   I*
  22     0     0.0 000   I
  24     0     0.0 000   I
  26     0     0.0 000   I
  28     0     0.0 000   I
 >30     0     0.0 000   I
```

```
*****   FINNOMOIST   *****

SORTING PROGRAM :

1.8.1980  15.00 1 56321789 345 45MM 175MM

TOTALCOUNT =   345; LENGTH =   1725M, VOLUME 13.58M3

                                          PCS %PCS   RM

1 3 MOISTURE AVERAGE UPPER 20.5             0  0.0   000
2 3 LENGTH           LOWER 400             25  7.2   095
3 4 MOISTURE MAXIMUM UPPER 20              29  8.4   145

SUMS OF OFF-SORTED                         54 15.6   240
```

Table 6

Infrared method property list

Infrared reflectance spectroscopy
(1 - 2.5μm (near IR))

A -- Optically observing the characteristic stretching frequencies of the water molecules in the samples

B -- Independent of material density, grain or orientation

C -- Low sensitivity to sample temperature

D -- Sensitivity over entire rnge of MC (0 - 100+%)

E -- Field penetration of sample less than 0.5 mm gauge only reads MC at surface of material

---

System examples

Paper MC gauge
Composite furnish gauge
Hog fuel MC gauge

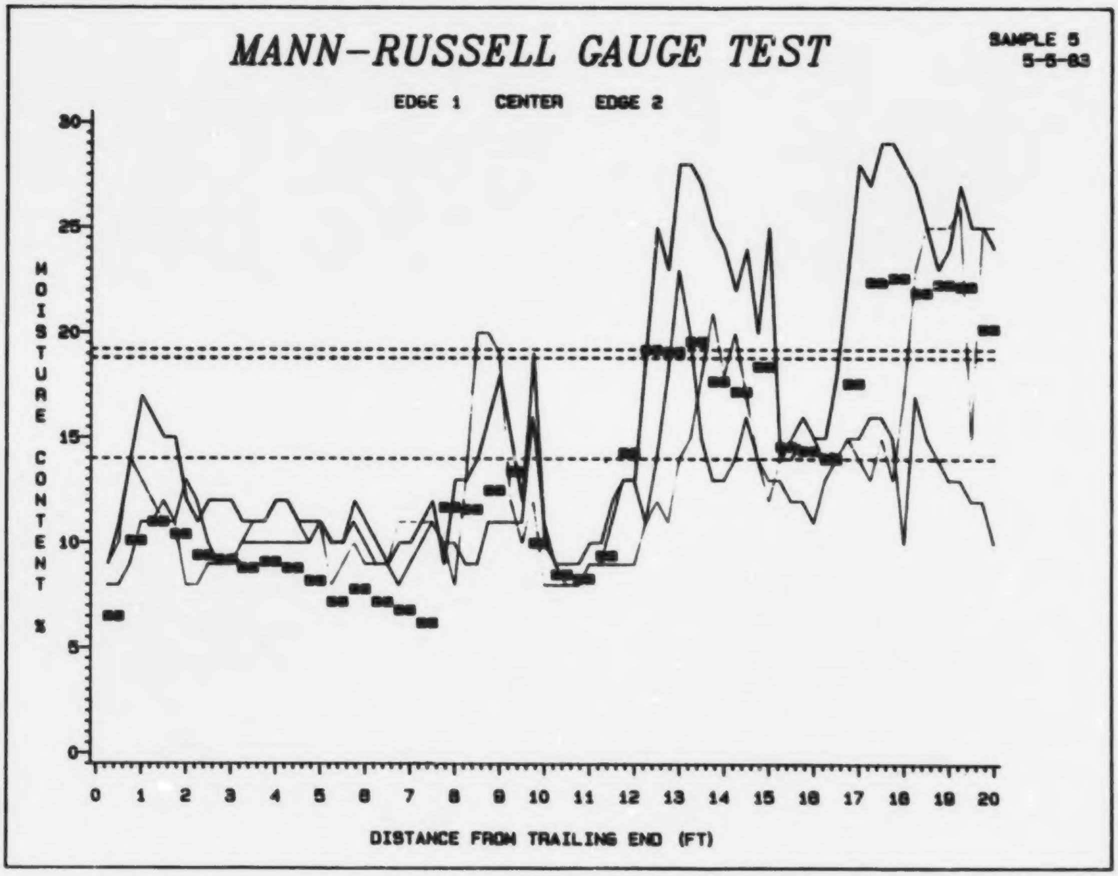

Figure 1. Plot of MC vs. position along a western hemlock board

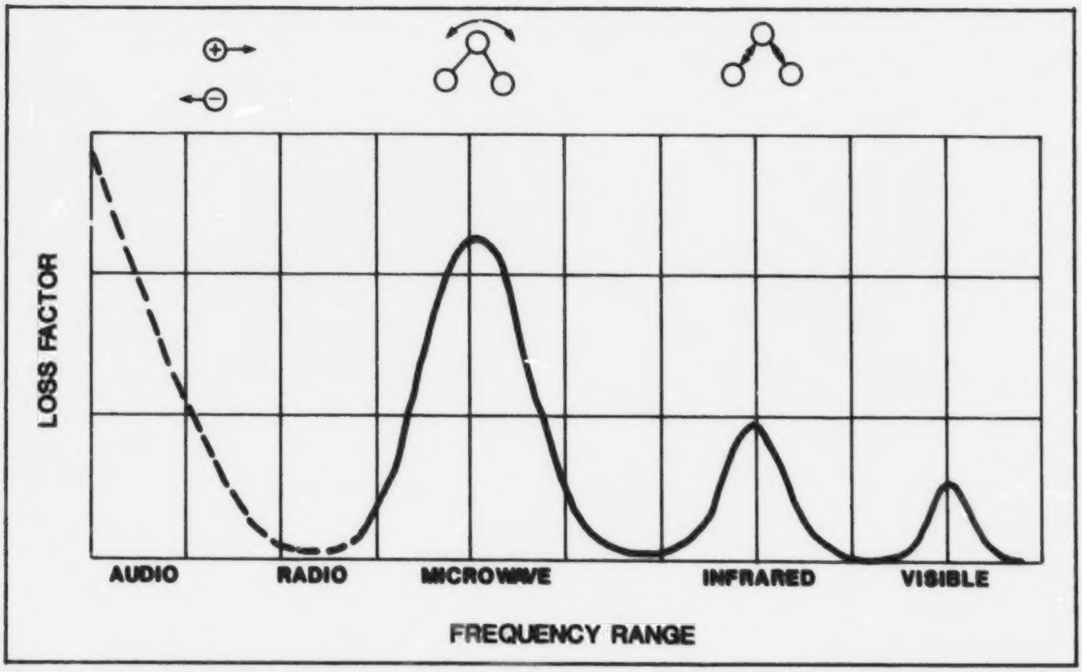
LOSS FACTOR
AUDIO
RADIO
MICROWAVE
INFRARED
VISIBLE
FREQUENCY RANGE

Figure 2. Schematic drawing of frequent vs. physical property being observed

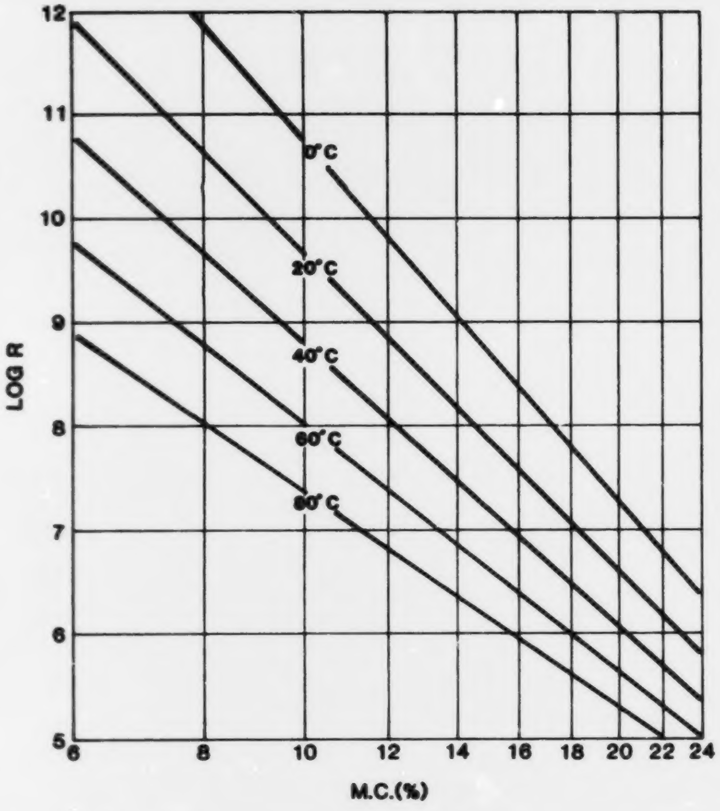

Figure 3. Resistance vs. MC for wood (along grain)

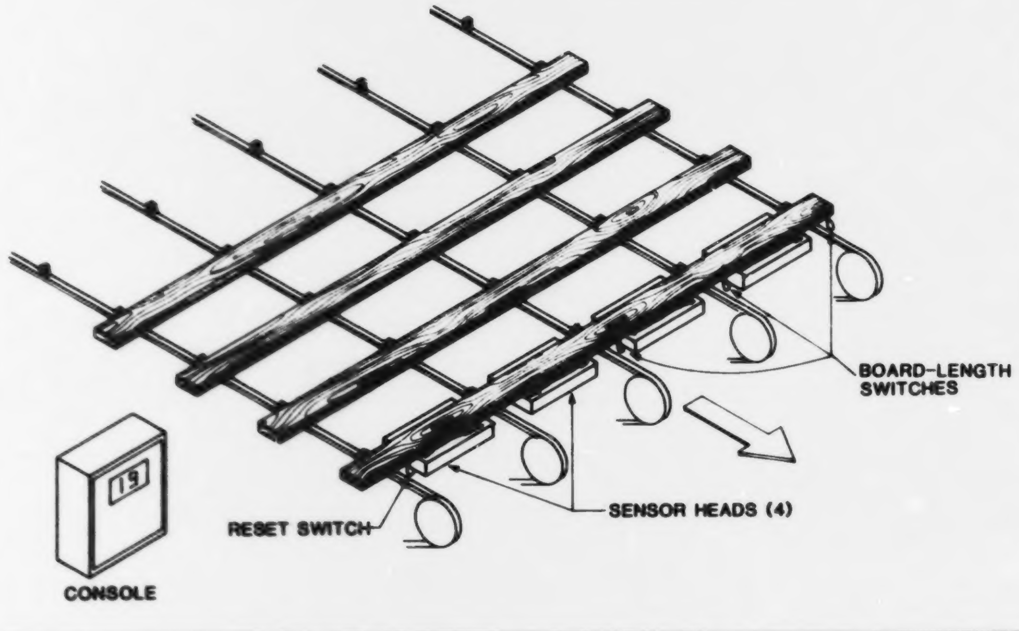
BOARD-LENGTH SWITCHES
SENSOR HEADS (4)
RESET SWITCH
19
CONSOLE

Figure 4. Strandberg installation schematic representation

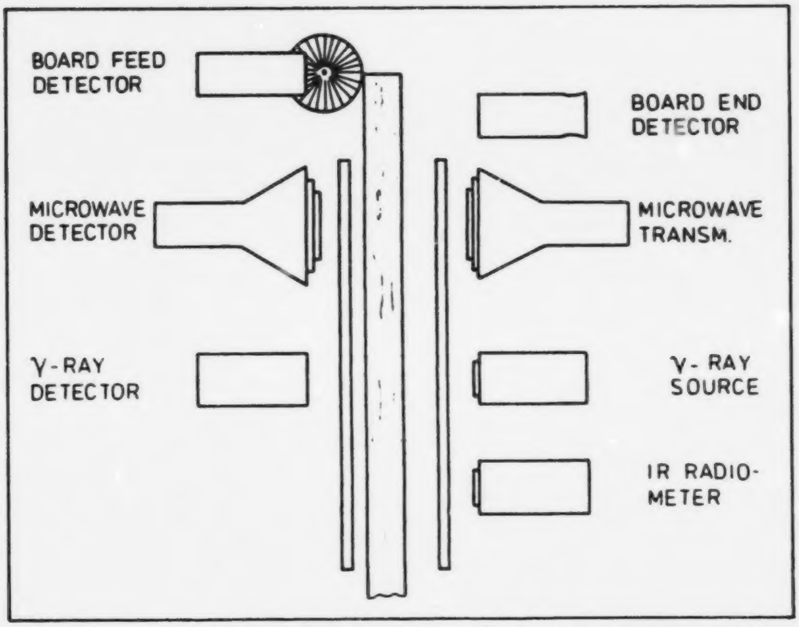
BOARD FEED DETECTOR
BOARD END DETECTOR
MICROWAVE DETECTOR
MICROWAVE TRANSM.
γ-RAY DETECTOR
γ-RAY SOURCE
IR RADIOMETER

Figure 5. Finnomoist sensor schematic representation

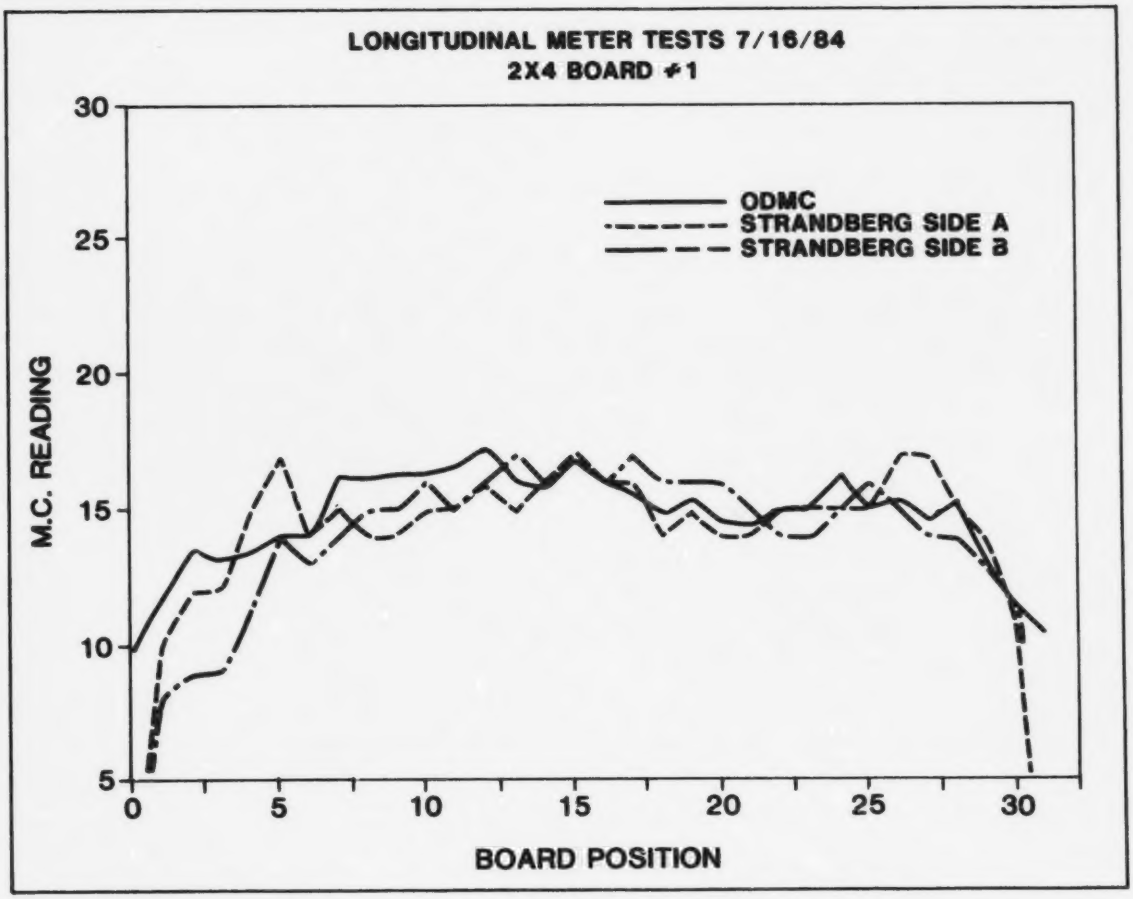

Figure 6. Longitudinal Strandberg MC plot

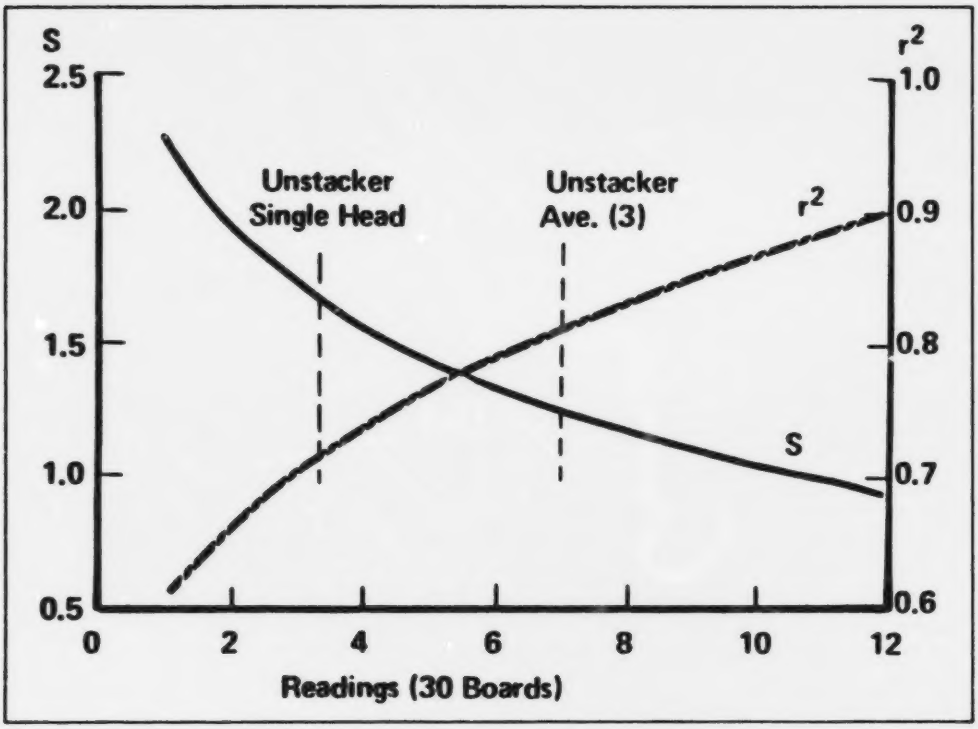

Figure 7. Strandberg statistical plot

Microwave Measurement of the Complex Dielectric Tensor of Anisotropic Slab Materials*

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Y.H. Yen, Bell Communications Research , Inc., Holmdel, NJ
W.L. James, Forest Products Laboratory, Madison, WI

Linearly polarized electromagnetic wave incident on an anisotropic material suffers attenuation, phase change, and depolarization upon transmission through or reflection from the material. Here it is shown how the measured electrical properties of a wave transmitted through dimension lumber can be used to determine the complex dielectric tensor. The theory, which applies equally to other lossy and anisotropic materials such as man-made composites having 2 x 2 uniaxial tensor, is couched in terms of the measurable attenuation, phase change, and depolarization.

A microwave measurement system has been developed for measuring these parameters. Results are given for extensive experiments, conducted at 4.81 GHz on Douglas-fir, for moisture contents ranging from dry to complete saturation. The technique shows considerable promise as an accurate nondestructive diagnostic tool for evaluating the electrical, and hence the physical and mechanical properties of semi-transparent anisotropic materials.

Theory

The theory for anisotropic media consisting of a mixture of dielectrics is scant, but some special cases were summarized by Tinga (1969). The abbreviated theory presented here is couched so as to be most easily related to the experimental parameters which can be measured.

Two-dimensional anisotropy is assumed, i.e., the z and y axes are aligned normal to the fibers as shown in Figure 1, and the x axis is parallel (||) to the fibers. Thus, a 2 x 2 dielectric tensor

$$\epsilon = \begin{pmatrix} \ddot{\epsilon}_{xx} & \ddot{\epsilon}_{xz} \\ \ddot{\epsilon}_{zx} & \ddot{\epsilon}_{zz} \end{pmatrix} \qquad (1)$$

is used where each element of the tensor is complex, i.e., $\ddot{\epsilon}_{xx} = \epsilon'_{xx} - j\epsilon''_{xx}$, etc., for an assumed $e^{j\omega t}$ time dependence. The wave equation is

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$$\bar{\nabla} \times \bar{\nabla} \times \bar{E} - \beta_0^2 \tilde{\epsilon}\bar{E} = 0. \qquad (2)$$

Assuming TEM plane waves and $\frac{\delta}{\delta x} = \frac{\delta}{\delta z} = 0$ (locally homogeneous in x- and z-directions) then (2) becomes

$$\left(\frac{d^2\bar{E}}{dy^2}\right) + \beta_0^2 \tilde{\epsilon}\bar{E} = 0 \qquad (3)$$

where $\beta_0^2 = \omega^2 \mu_0 \epsilon_0$, and the medium is assumed to be magnetically isotropic with $\mu = \mu_0$.

We introduce the complex propagation constants $\hat{\gamma}_{\parallel}(=\alpha_{\parallel} + j\beta_{\parallel})$ and $\hat{\gamma}_{\perp}(=\alpha_{\perp} + j\beta_{\perp})$ for the x- and z-components, respectively. The $\parallel$ and $\perp$ notations refer to when the incident E-field components are parallel and perpendicular to the grain. Then, both $\alpha_{\parallel}$ and $\beta_{\perp}$ are significantly larger than $\alpha_{\perp}$ and $\beta_{\perp}$, respectively. This is especially true if significant losses are present, since the magnitude of $\hat{\epsilon}_{\parallel}(\hat{\epsilon}_{xx})$ is significantly greater than the magnitude of $\hat{\epsilon}_{\perp}(\hat{\epsilon}_{zz})$.

As the wave propagates through the material, the z-component $E_z(y)$ of the electric field gives rise to a new field e_x in the x-direction, thereby generating an elliptically polarized wave. This is because the off-diagonal (cross-coupling) entries of the dielectric tensor are nonzero. Moreover, this new coupled field $e_x(y)$ is in quadrature phase with $E_z(y)$, a well known property of polarization ellipses. Similarly, we get a field $e_z(y)$ in the z-direction which is coupled to and in quadrature phase with $E_x(y)$.

Thus, since the incident field has x and z components in general, there are two elliptically polarized modes travelling in the +y-direction. Let $p_{\perp}(y)$ and $p_{\parallel}(y)$ denote the signed ratios $|e_x(y)/E_z(y)|$ and $|e_z(y)/E_x(y)|$, respectively, as shown in Figure 2. The signs of $p_{\perp}(y)$ and $p(y)$ will be decided depending on the nature of ellipticity (left-handed or right-handed) of the fields. These can be determined experimentally.

The electric field can then be expressed in the form

$$\bar{E}_{(y)} = \begin{pmatrix} e^{-\hat{\gamma}_{\parallel} y} & jp_{\perp}(y)e^{-\hat{\gamma}_{\perp} y} \\ jp_{\parallel}(y)e^{-\hat{\gamma}_{\parallel} y} & e^{-\hat{\gamma}_{\perp} y} \end{pmatrix} \begin{pmatrix} E_{xo} \\ E_{zo} \end{pmatrix} \qquad (4)$$

which is generated by the incident fields in both the x- and z-directions, E_{xo} and E_{zo}. Substituting (4) into (3) yields a matrix equation similar to (4) in which the four complex elements of the coefficient matrix must all be zero. This results in eight equations for determining the eight unknowns of the complex dielectric tensor (1).

$$\epsilon'_{xx}(y) = -((\alpha^2_{\parallel} - \beta^2_{\parallel})/\beta^2_0 + \epsilon''_{xx}p_{\parallel}(y))$$

$$\epsilon''_{xx}(y) = (2\alpha_{\parallel}\beta_{\parallel}/\beta^2_0) + \epsilon'_{xz}p_{\parallel}(y)$$

$$\epsilon'_{xz}(y) = (1/D_{\epsilon})((2\alpha_{\parallel}\beta_{\parallel} - 2\alpha_{\perp}\beta_{\perp})p_{\perp}(y) + 2\beta_{\perp}p'_{\perp}(y))$$

$$\epsilon''_{xz}(y) = (1/D_{\epsilon})((\alpha^2_{\parallel} - \beta^2_{\parallel} - \alpha^2_{\parallel} + \beta^2_{\parallel})p_{\perp}(y) + 2\alpha_{\perp}p'_{\perp}(y) = p''_{\perp}(y)) \qquad (5)$$

$$\epsilon'_{zx}(y) = (1/D_{\epsilon})((2\alpha_{\parallel}\beta_{\parallel} - 2\alpha_{\perp}\beta_{\perp})p_{\parallel}(y) - 2\beta_{\parallel}p'_{\parallel}(y)$$

$$\epsilon''_{zx}(y) = (1/D_{\epsilon})((\alpha^2_{\parallel} - \beta^2_{\parallel} - \alpha^2_{\perp}\ \beta^2_{\perp})p_{\parallel}(y) - 2\alpha_{\parallel}p'_{\parallel}(y) + p''_{\parallel}(y))$$

$$\epsilon'_{zz}(y) = -((\alpha^2_{\perp} - \beta^2_{\perp})/\beta^2_0 - \epsilon''_{zx}p_{\perp}(y))$$

$$\epsilon''_{zz}(y) = (2\alpha_{\perp}\beta_{\perp}/\beta^2_0) - \epsilon'_{zx}p_{\perp}(y)$$

where $D_{\epsilon} = \beta^2_o[1 - p_{\perp}(y)p_{\parallel}(y)]$, $p'(y) = dp/dy$ and $p''(y) = d^2p/dy^2$ for both $p_{\parallel}$ and $p_{\perp}$. Note that in this analysis multiple internal reflections have been neglected. Corrections which account for these effects, as well as the reflection from the front interface, can be made as discussed below.

Experimental Procedure and Data Analysis

By orienting the specimens so that the incident field is parallel and then perpendicular to the grain, zero-th order values for $P_{\parallel}(y)$, $\alpha_{\parallel}(y)$ and $\beta_{\parallel}(y)$ and then $p_{\perp}(y)$, $\alpha_{\perp}(y)$ and $\beta_{\perp}(y)$ can be easily measured. Note that while $\gamma_{\parallel,\perp}$ are constants with y, $p_{\perp,\parallel}(y)$ are functions of y, e.g., $p_{\perp,\parallel}(0) = 0$ and $p_{\perp,\parallel}(\infty)$ = constant which is less than unity. In view of (5), $p_{\perp,\parallel}(y)$ and $p''_{\perp,\parallel}(y)$ are involved in the solution for the dielectric tensor, representing higher order effects which may be negligible in some cases.

If necessary when testing wood, $P_{\perp,\parallel}(y)$ can be measured over the range of moisture contents where $p'_{\perp,\parallel}(y)$ and $p''_{\perp,\parallel}(y)$ are significant. This can be done by stacking thin slabs of wood, all cut from the same board and stabilized at the same moisture content. These data tables can be stored for retrieval as needed. Assuming that the moisture content can be determined to reasonably good accuracy using the zero-th order solution as obtained by assuming $p'_{\perp,\parallel}$ and $p''_{\perp,\parallel}$ are negligible, good approximations to $p'_{\perp,\parallel}$ and $p''_{\perp,\parallel}$ can be read from the stored tables. These can be used in (5) to find first or higher order solutions of $\tilde{\epsilon}$.

The preceding theory gives the field in the first pass through the slab by neglecting multiple internal reflections for simplicity. To find the fields transmitted through the slab, reflections between the slab and air must be included. This can be done using an approximate method involving a simple iterative procedure to find the first or higher order solutions. The zero-order solution as found from (5) is first used to calculate the reflection coefficients $R_{\perp}$ and $R_{\parallel}$ for the field components which are perpendicular and parallel to the grain, respectively. Then the transmitted field components at each interface are corrected according to the transmission factor, $T_{\perp} = 1 - R_{\perp}$, etc. In turn, these R and T factors are used to correct the measured parameters and (5) is used again to find the first order corrected tensor.

This iteration procedure is repeated until convergence is achieved, typically about three times. The resulting attenuation and phase change are then divided by the specimen thickness, W, giving the iterated attenuation constants $\alpha_{\perp,\parallel}$ and phase constants $\beta_{\perp,\parallel}$ which are now independent of thickness. The dielectric tensors in the following are the results after such corrections.

Experiments

Details of the instrumentation system used to measure the amplitude, phase, and polarization of the field transmitted through the slab material are described elsewhere (King and Yen, 1981 and Yen, 1981). For present purposes, it is sufficient to remark that the electric field was measured using a modulated dipole probe and a coherent (homodyne) detection system. As shown in Figure 3, the board specimens were illuminated with a vertical incident field $\vec{E}$ which was essentially a plane wave.

Square specimens (8 x 8 inches) were mounted on a rotatable test apparatus and surrounded with microwave absorbing material to minimize fields diffracted around the specimen edges. The experiments were carried out in a small anechoic chamber. The dipole probe, which could also be rotated about the normal to its axis, was placed 1.5 cm from the back side of the board to minimize electrostatic coupling with the wood.

As the anisotropy of the wood tends to cause the transmitted field, $\vec{E_t}$, to be aligned perpendicular to the grain, the specimens were rotated so that the transmitted field was aligned with the incident field, i.e., $\theta = 0$ in Figure 3. This ensures that the true grain angle, θ, as well as E_{xo}, is zero. The amplitude and phase change relative to the absence of the test structure were then measured for this $\perp$ position, followed by a measurement of $p_{\perp}$ obtained by rotating the dipole probe by $\pi/2$.

The test specimen was then removed and rotated by $\pi/2$, and the measurement procedure was repeated to determine the amplitude and phase when the incident field is $\parallel$ to the grain so that E_{zo} is zero. Then, the dipole was rotated $\pi/2$ to measure $p_{\parallel}$. These data were then used in (4) and the iteration procedures applied to account for reflections as noted earlier.

Results

Although several species of both hard and coniferous woods were tested, only the results for Douglas-fir are given here. Results for other species are given by Yen (1981). The following data represents the averages of results obtained for many specimens having varying moisture content (MC) as determined by weight.

Figure 4 shows the loss and phase constants which were deduced. The fact that $\alpha_{\parallel}$ and $\beta_{\parallel}$ are substantially larger than $\alpha_{\perp}$ and $\beta_{\perp}$, respectively is clearly evident.

The real dielectric constants $\epsilon'_{\parallel}(=\epsilon'_{xx})$ and $\epsilon'_{\perp}(=\epsilon'_{zz})$ and corresponding loss tangents are shown in Figure 5, and Figure 6 shows the loss factors $\epsilon''_{\parallel,\perp}$. Note that both ϵ' and ϵ'' increase exponentially for mc below the fiber saturation point (about 25 percent), and increase in a nearly linear manner above this point.

Above fiber saturation, the more rapid increase is due to more free water which has an extremely high dielectric constant. Also note that $\epsilon'_{\parallel}$, $\epsilon''_{\parallel}$ and tan $\delta_{\parallel}$ are all substantially greater than the perpendicular case, particularly for all MC above fiber saturation.

Finally, note that tan $\delta_{\parallel,\perp}$ are both substantially larger than tan δ for free liquid water. Presumably, this is because the polar water molecules suffer an increased degree of friction due to the cellulose of the wood fibers. Also, the microwaves are severely scattered by the macroscopic structure of the water laden fibers, thereby increasing the losses. Different fiber structures (e.g., porous, granular, and powdered) can bind water in many different ways depending on density, temperature, and chemical and physical composition (Tinga, 1969).

The dielectric and loss tangent tensors for Douglas-fir are given below for MC's ranging from 0 to 150 percent by weight.

$$\begin{array}{ccc}
 & \text{Dielectric tensor} & \text{Loss tangent} \\
\text{mc (\%)} & \begin{bmatrix} \hat{\epsilon}_{xx} & \hat{\epsilon}_{xz} \\ \hat{\epsilon}_{zx} & \hat{\epsilon}_{zz} \end{bmatrix} & \begin{bmatrix} \tan\delta_{xx} & \tan\delta_{xz} \\ \tan\delta_{zx} & \tan\delta_{zz} \end{bmatrix} \\
0 & \begin{bmatrix} 1.9-j0.053 & 0.00042+j0.0025 \\ 0.00024+j0.0018 & 1.68-j0.02 \end{bmatrix} & \begin{bmatrix} 0.0279 & -6 \\ -11.6 & 0.012 \end{bmatrix} \\
6 & \begin{bmatrix} 2.35-j0.15 & 0.0018+j0.0075 \\ 0.0027+j0.01 & 1.9-j0.095 \end{bmatrix} & \begin{bmatrix} 0.064 & -4.2 \\ -4.2 & 0.051 \end{bmatrix} \\
12 & \begin{bmatrix} 2.73-j0.7 & 0.00524+j0.00784 \\ 0.0123+j0.0184 & 2.156-j0.31 \end{bmatrix} & \begin{bmatrix} 0.253 & -1.5 \\ -1.5 & 0.144 \end{bmatrix}
\end{array}$$

$$52 \quad \begin{bmatrix} 11.7-j4.8 & 0.03+j0.049 \\ 0.2+j0.33 & 6.2-j2.2 \end{bmatrix} \qquad \begin{bmatrix} 0.41 & -1.63 \\ -1.65 & 0.355 \end{bmatrix}$$

$$150 \quad \begin{bmatrix} 38.3-j25.2 & 0.96+j0.93 \\ 3.46+j3.36 & 23.8-j10.8 \end{bmatrix} \qquad \begin{bmatrix} 0.68 & -0.97 \\ -0.97 & 0.45 \end{bmatrix}$$

Note that the "loss tangents" for the off-diagonal terms are negative and greater than unity except for green wood, in contrast to the loss tangents of the diagonal terms which are positive and less than unity. Positive values of tan δ for the diagonal terms signify a true loss, while the negative values for the off-diagonal terms imply the "coupling" from the other electric field component. Thus, it denotes a "gain" rather than a "loss". Larger "negative" values for the off-diagonal terms imply stronger cross-coupling (or depolarization). For green wood, free water presumably dominates the effect on the microwaves, and the anisotropy (due to the grain angle) is reduced, giving less depolarization.

It is important to observe that the off-diagonal terms of the dielectric tensor are much more sensitive to the MC, especially for high MC, than the diagonal terms. They will undoubtedly play a key role in future measurement of the anisotropic properties of materials.

In theory, the off-diagonal terms should be symmetrical about the diagonal. The fact that they are not is likely due to the erroneous manner in which $p_\parallel$ and $p_\perp$ were measured. In the procedure outlined in the "Experiments" section, $p_\parallel$ and $p_\perp$ were actually measured by rotating the dipole probe approximately $\pi/2$ to achieve a minimum in the detected response, rather than rotating it exactly by $\pi/2$. These results show that great care must be exercised in measuring $p_{\parallel,\perp}$ in order to accurately quantify the off-diagonal terms of the matrix. In spite of this problem, the conclusion that the off-diagonal terms are sensitive diagnostic indicators of the anisotropic properties (e.g., due to moisture) still applies.

Conclusion

The results given here have demonstrated that microwaves can yield much insight into the physical properties of semi-transparent anisotropic materials such as wood and composites. Besides their use in nondestructive evaluation where parameters like moisture content, specific gravity (or density), and grain or fiber orientation are of primary interest, it is also possible to infer properties about the physics of anisotropic mixtures. This is a more basic than applied application. In either case, a common factor is the complex dielectric tensor.

While these results are quite conclusive insofar as wood is concerned, more research into the physics of anisotropic mixtures is indicated. To this end, as well as in applied nondestructive evaluation, improvements in instrumentation, measurement techniques, and data analysis are needed. In particular, the use of a swept frequency would greatly enhance insight. Also, real-time data collection, analysis, and graphic display would make this a powerful tool indeed.

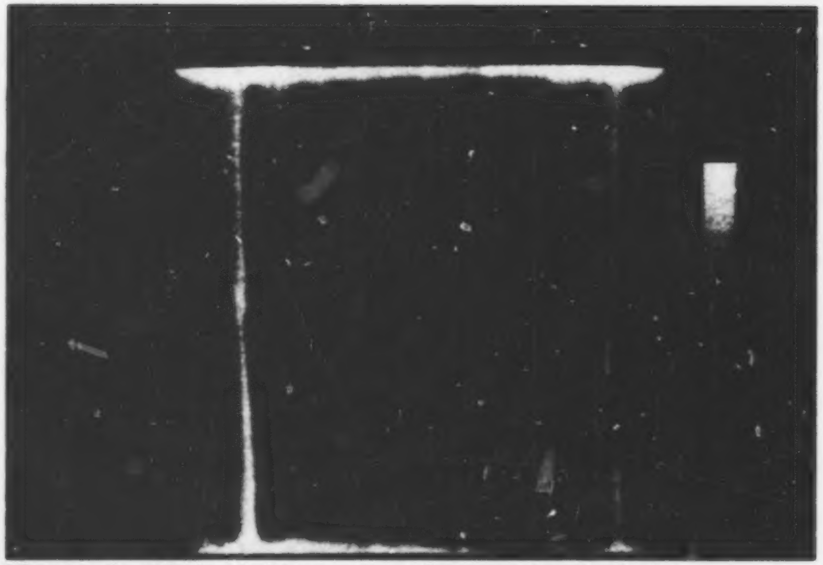

Figure 2. Digital line scan of green hemlock log.

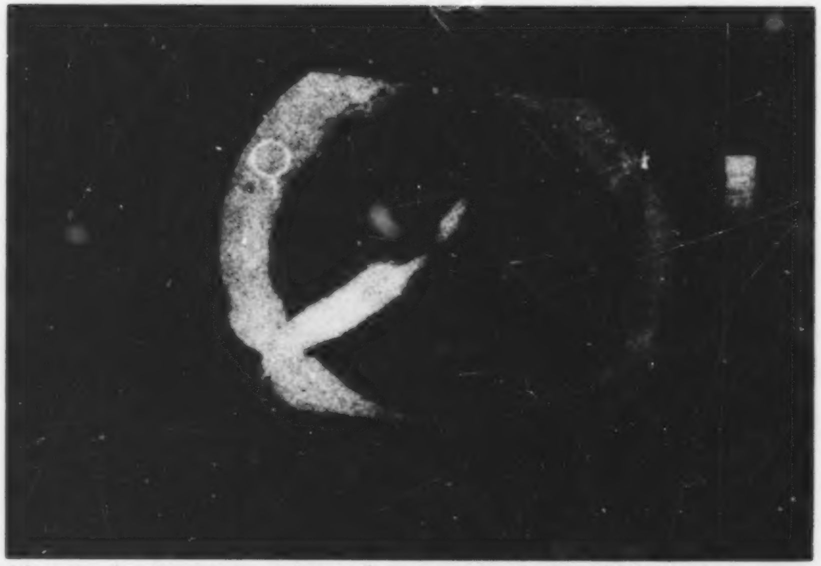

Figure 4. Cross-section of green hemlock with knot, sapwood is solid white in image.

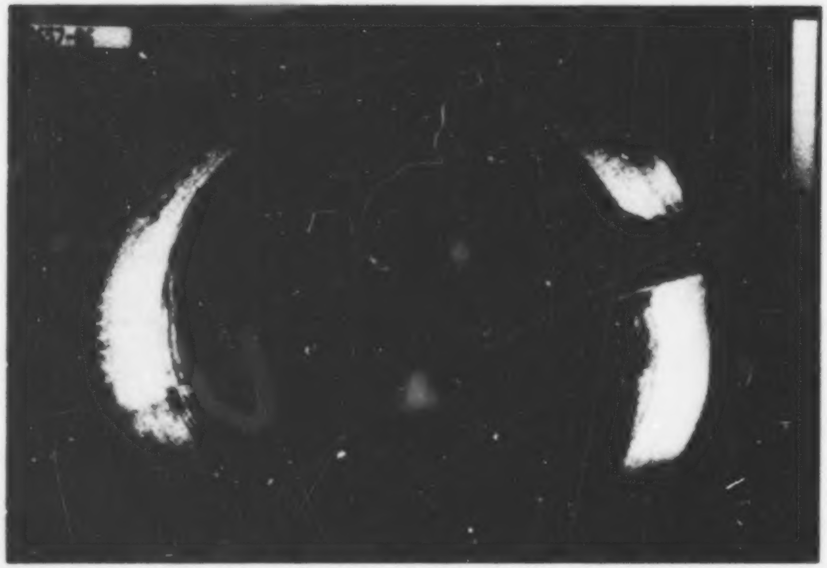

Figure 7. NMR scan of green hemlock at same position as Figure 4.

Plate 1

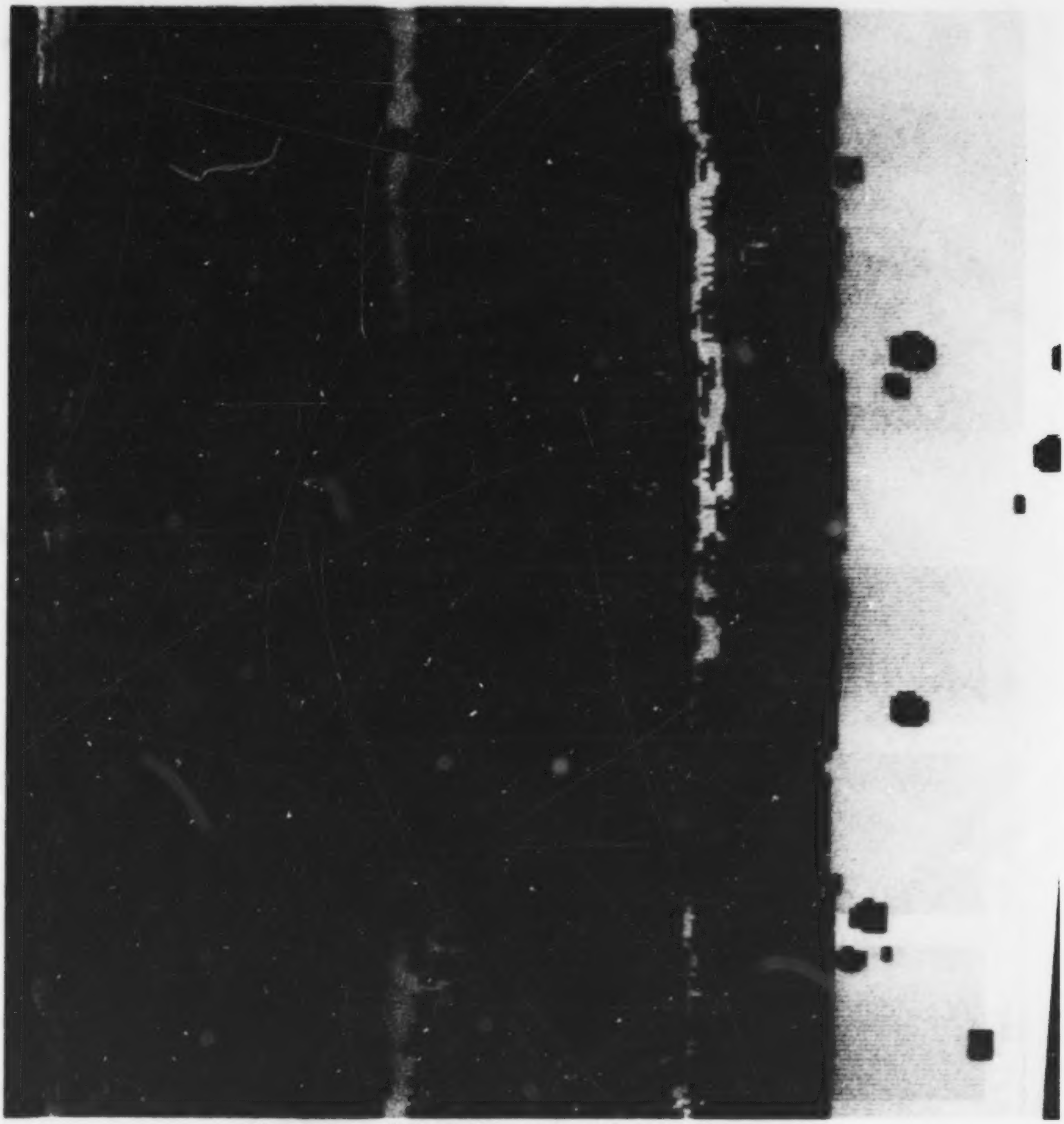

Figure 1. "Q" Option: knot and split detection.

Plate 4

REFERENCES

James, W.L. and D.W. Hamill. 1965. Dielectric properties of Douglas fir--measured at microwave frequency. Forest Prod. J. 15(2):51-56.

King, R.J. and Y.H. Yen. 1981. Probing amplitude, phase and polarization of microwave field distributions in real-time. IEEE-MTT 29(11):1225-1231.

Tinga, W.R. 1969. Multiphase Dielectric Theory Applied to Cellulose Mixtures. Ph.D. Thesis, University of Alberta.

Yen, Y.H. 1981. Microwave Electromagnetic Nondestructive Testing of Wood in Real Time. Ph.D. Thesis, University of Wisconsin.

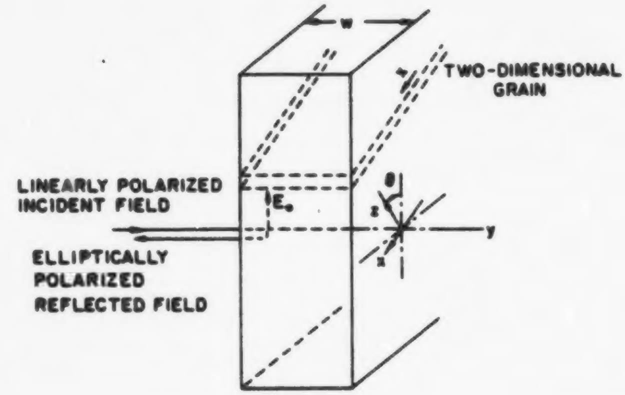
w
TWO-DIMENSIONAL GRAIN
LINEARLY POLARIZED INCIDENT FIELD
E_o
θ
z
y
x
ELLIPTICALLY POLARIZED REFLECTED FIELD

Figure 1. Anisotropic slab showing coordinate axes used and orientation of two-dimensional grain.

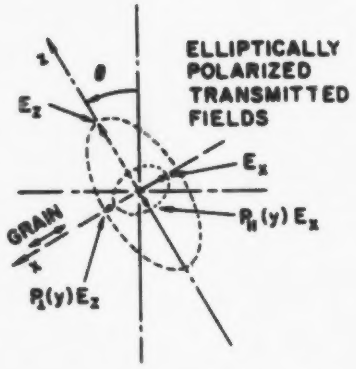
z
θ
ELLIPTICALLY POLARIZED TRANSMITTED FIELDS
E_z
E_x
$R_{\parallel}(y) E_x$
GRAIN
x
$R_{\perp}(y) E_z$

Figure 2. In general, two elliptically polarized modes propagate through an anisotropic medium, superimposed on the coordinates shown in Figure 1.

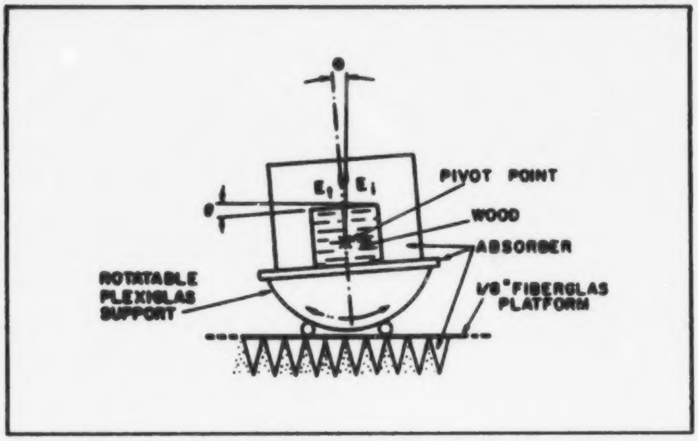
E∥
E⊥
θ
PIVOT POINT
WOOD
ABSORBER
ROTATABLE PLEXIGLAS SUPPORT
1/8" FIBERGLAS PLATFORM

Figure 3. Test jig for mounting and rotating the wood specimen.

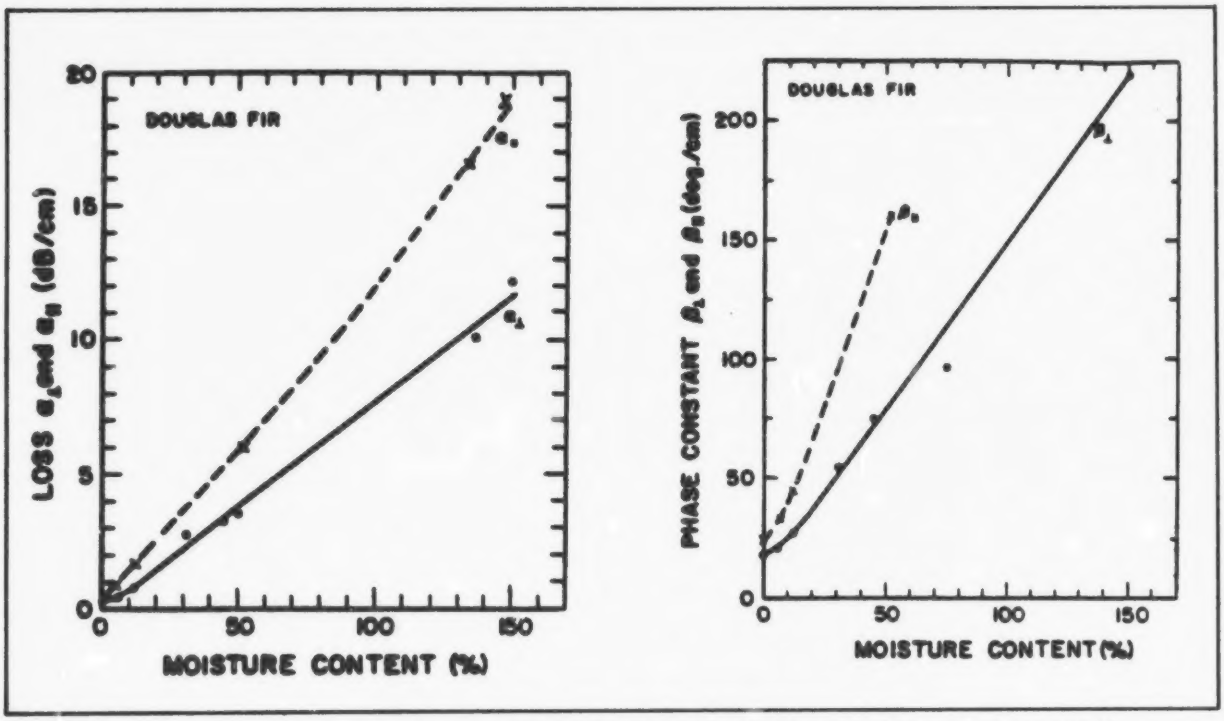

Figure 4. Loss and phase constants for microwave (4.81 GHz) propagation through Douglas-fir.

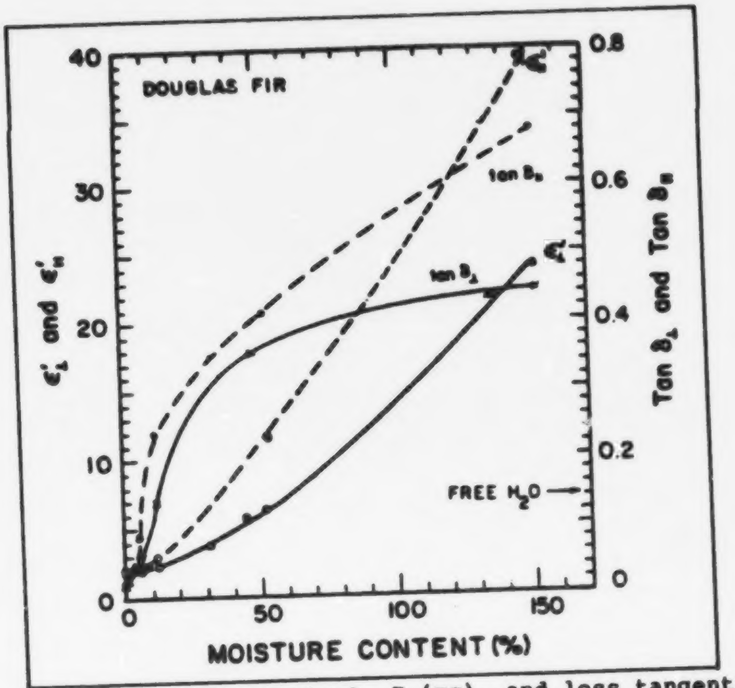

Figure 5. Real dielectric constant, E (mc), and loss tangents, $\tan\delta$, for electric field components which are parallel (∥) and perpendicular (⊥) to the grain of Douglas-fir.

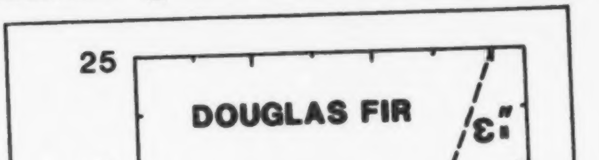

Figure 6. Loss factor "(mc), parallel (∥) and perpendicular (⊥) to the grain of Douglas-fir.

Video Laser Shape– Potential Forest Industry Applications

L. Chaisson, Applied Scanning Technology, Mountain View, CA

By combining the precision of a helium-neon laser with the high data capacity of a television camera, AST has developed a unique device (US Patent #4,188,544) for accurately generating shape contours of moving and stationary objects. Shape contours are obtained at a rate of 60 per second and may be used for a variety of measuring, cutting, sorting and inspection applications.

A typical application is shown in Figure 1 in which pencil stock material is scanned on a conveyor for shape and sorted into five categories at a rate of 150 blocks per minute.

Concept

The drawing (Figure 1) shows a thin sheet of laser light intersecting a workpiece, which is viewed by a TV camera with a special filter to eliminate the effects of ambient light. The camera is oriented at about 45 degrees with respect to the laser plane to provide a depth perspective.

One means for visualizing the VLS geometry is to view the camera video signal on a TV monitor. As the workpiece moves through the laser light, the camera "sees" contours representing the shape of the object with total system accuracies better than 0.010 inches.

Electronics

The camera output is fed to a special video processor that digitizes the shape contour for transfer to the microcomputer. The microcomputer is programmed to apply the shape data to fit the specific application.

Calibration

VLS is completely self-calibrating. The camera observes the laser light intersection with reference surfaces, of known positions and dimensions, placed in the field-of-view adjacent to the workpiece. Data from these surfaces is continuously updated to compensate for possible drifts in either the camera electronics or position. These surfaces, which are also shown in the drawing, can take almost any convenient form.

Diagnostics

VLS comes equipped with thorough diagnostics which include direct video display, calibration status, power supply lights and extensive diagnostic software for quickly testing all components of the system.

In addition, calibration and material data (maximum, minimum and average width, height, volume, or edge location) can be displayed on the monitor in either text or graphics form.

Other Features

The video processor can multiplex the output from up to eight cameras as required in applications where parallel observations of similar processes is desired. Also, each camera can observe the line contours from multiple laser sources.

In some extensive applications, additional computation capability may be required. Interfaces to a wide variety of 16 or 32 bit CPU's are available. Application software and engineering to provide a turn-key installation can be provided.

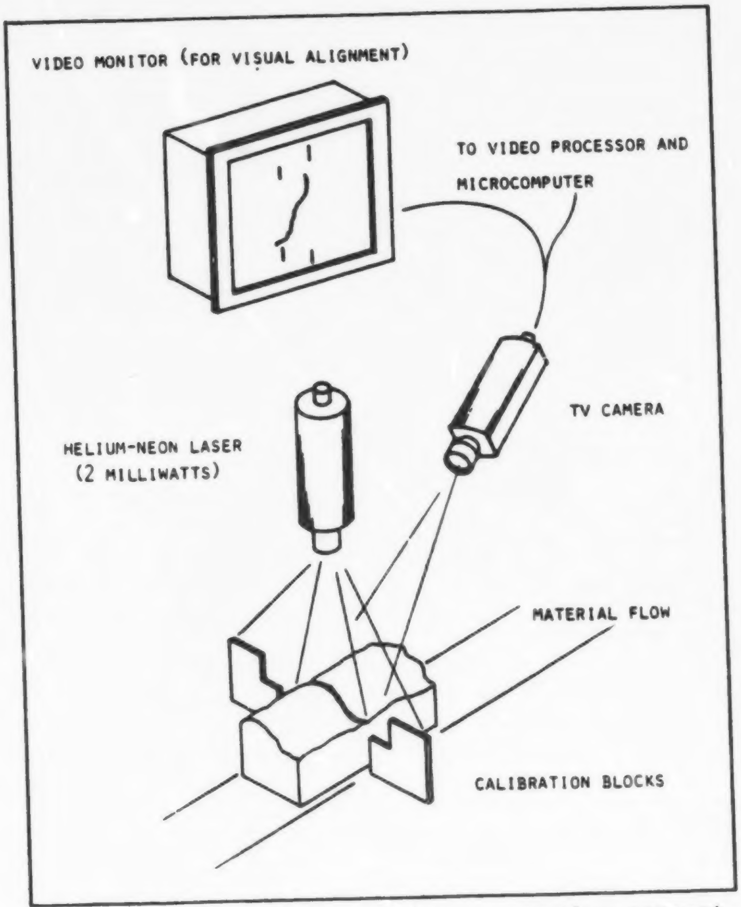
VIDEO MONITOR (FOR VISUAL ALIGNMENT)
TO VIDEO PROCESSOR AND MICROCOMPUTER
TV CAMERA
HELIUM-NEON LASER (2 MILLIWATTS)
MATERIAL FLOW
CALIBRATION BLOCKS

Figure 1. Video-laser shape--scanning concept

Application of Laser/Optics and Fiber Optics to Scan Flitches for Optimized Edging or Trimming

David C. Carlson, Trienco Automation Systems Company, Seattle, WA

As the subject of this seminar is scanning, it seems appropriate as an introduction to mention three areas where our company has pioneered the introduction of scanning technology to the wood products industry.

In 1969 Trienco, Inc., introduced air-coupled ultrasound to the panel industry in the form of a quality assurance system for identifying internal defects. This system is now well established with over 150 installations.

Following the introduction of the ultrasonic defect detector, research followed with laser optics for a precise non-contact measuring device. This research culminated in the first mill installation of the optical image displacement thickness gauge in 1974. Although this technology is now 10 years old, it remains technically the most advanced.

The basic principle of this scanner will be the first portion of this paper.

Currently, Trienco Automation Systems Company is nearing the first mill installation of fiber optics scanning for trimmer optimization. Fiber optics is the second portion. Referring to Figures 1, 2 and 3, I will describe as simply as possible the operation of the laser/optics scanner.

The upper portion is the measuring device which is aproximately 2 x 2 x 24-in. It contains, on the right side, a low power helium neon laser which projects a laser beam on a precise 45 degree angle. The left side of the device contains an optical array.

Referring to Figure 1, note the laser intercept point to the surfaces of the flitch. The center of this spectacular scattering of light is the reference point which is sensed by the photo array. By drawing a line representing a thicker piece, it is readily apparent that the reference point has now shifted horizontally. By simple trigonometry the horizontal distance is equal to the vertical, thus we have measured the distance D1 to the surface.

Figure 3 shows the addition of a line-measuring device underneath the flitch measuring D2. The thickness is the distance between the upper and lower scan heads minus the sum of D1 and D2. This measurement technique is called 'differential measurement' and allows non-contact measurement unaffected by vertical board movement. As long as the flitch is within the measurement window, the system is capable of measuring better than ± 0.005-in. A measurement rate of 2,000 measurements per second effectively eliminates error caused by vibration.

The fiber optics scanner operates on similar physical principles to the laser/optics scanner.

Fiber optics are, simply put, tubes which transmit light. The application which the fiber optics plays in imaging scanning is to eliminate the laser by providing the light source for the reference measuring point described previously. The technological development which the fiber optics scanner has introduced is an optical apparatus located at the terminal of each fiber optic wire which transmits a light beam through air to the surface of the flitch.

The advantages of this scanning principle when used in conjunction with the laser/optics scanner are twofold. By eliminating the lasers and using a single light source, the scanner can be configured to provide a scan zone or cross-section thickness profile at every one inch increment along the length of the piece. Secondly, for a normal 20 - 26-ft. application the scanner cost for a one inch increment is approximately one-seventh that of a system using the laser/optics scanner.

Turning to the optimizer edging and/or trimming application of this scanning technology, there is a point which is crucial if one is to achieve the theoretical maximum dollar recovery. The scanners described are geometric scanners. That is they directly measure the shape of the flitch. Other scanning techniques are photographic scanners. They digitalize an image and apply logic to aid in the solution, much as a human operator would. On rough green flitches, accurately knowing the geometric profiles and allowing for shrinkage, planer allowance, allowable edge and face wane permit an exact fit for the finished lumber size.

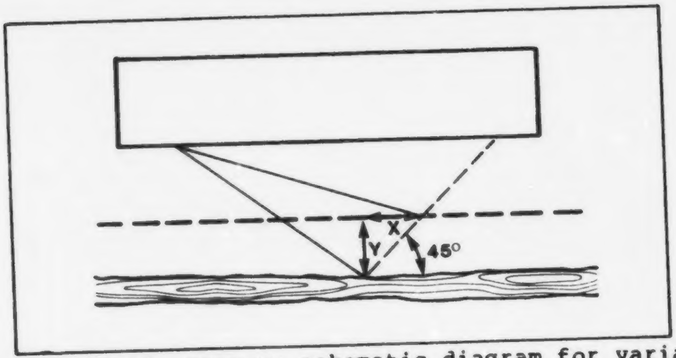

Figure 1. Laser/optic scanner schematic diagram for variable height (thickness).

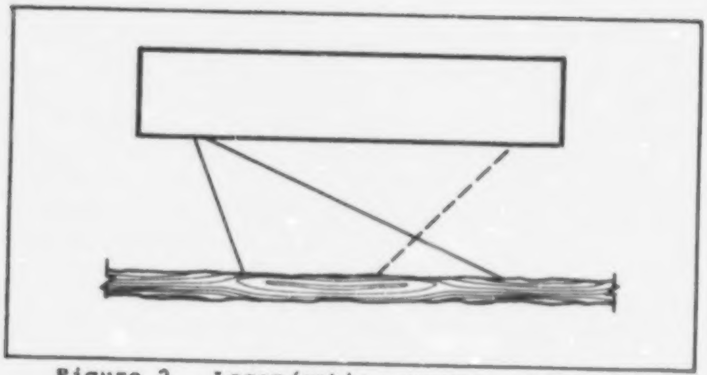

Figure 2. Laser/optic scanner schematic.

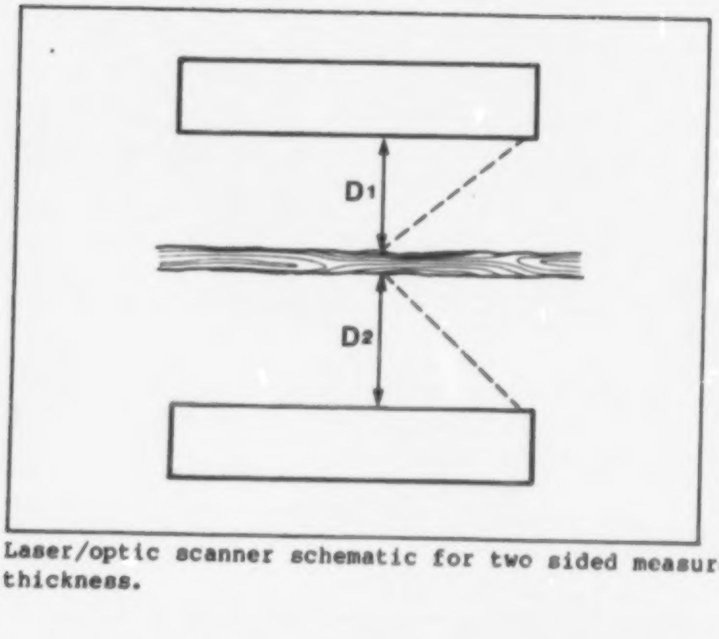

Figure 3. Laser/optic scanner schematic for two sided measurement of thickness.

Optimizing Lumber Recovery Using Board Profile and Defect Detection Scanning Techniques

M.V. Maleta, SAAB Systems Inc., Seattle, WA

Although much of this presentation references the trimming application, the same scanning and computer hardware components are now being applied to the edging application.

SAAB Wood, our sister company in Sweden, has installed over 35 systems applying this scanning technique to edger optimization. SAAB Systems has installed eight systems for trimmer optimization, and has eight more on order. Three of the systems on order will be utilized for edger optimization, and all of them will be installed before the end of this year.

It seems a significant segment of the North American sawmill industry considers this a viable technology. The unique thing about the system is it has the future capacity, with some computer hardware and software upgrades, to utilize defect detection in the optimization process.

First, I will address SAAB's approach to optimization of the edger and trimmer using board profile scanning. Later, I will introduce the addition of defect detection scanning to the optimization process.

Optimization of the edger and trimmer is accomplished by following three basic steps:

- Seeing the board (or flitch).
- Making a decision on the optimum recovery solution.
- Carrying out the processing decision.

SAAB's optimizer system accomplishes these three important steps using recognition of board profile as a basis for deciding how to optimally trim, or edge, the board. Our system consists of four basic sub-systems:

- The scanner sub-system.
- The optimization sub-system.
- The information sub-system, and
- The control sub-system.

The scanner sub-system uses an Intel 8086 single board 16-bit microcomputer to collect board measurement data for the optimization sub-system. An 8085 single board 8-bit microcomputer functions as a shaft encoder interface to measure chain movement. Depending on the length of material being processed the system has up to four light sensitive SAAB cameras, working in sequence with alternately strobing gas charged neon lamp banks, for lumber profile measurement. There are also up to eight lasers which provide board thickness information using a simple triangulation method of measurement. This scanning technique allows precise non-contact three-dimensional measurement of lumber, at the trimmer for instance, at rates of sixty to seventy boards per minute.

After the data is collected it is passed on to the optimization sub-system which has a second Intel 8086 single board 16-bit microcomputer. Its function is to evaluate the board measurement data with sawmill wane and size parameters, and lumber prices to compute the optimum or most valuable decision. Once a decision is made, it is relayed to the control sub-system for implementation.

The information sub-system provides the communication path for processing decisions to the programmable controller, management reporting and user interaction with the system. The information sub-system hardware includes an Intel 8086 single board 16-bit microcomputer with 64K bytes of on-board memory; a hard copy printer which provides shift reports, diagnostic reports and system management data; a dual floppy drive for program and board data storage and a graphics terminal that allows user interaction and control.

In the event of power failure, a 64K byte battery back-up memory retains dynamic data such as production tallies, and assortment and calibration data. There is also a 256K byte extension of the 64K memory on the 8086 microcomputer card. With the battery back-up memory the information sub-system has 384K bytes of random access memory.

Operation

As singulated boards pass beneath the scanner frame, and through an invisible scan curtain, a number of things occur. Width, length, profile and end contour information is collected by utilizing alternating light sources and light sensitive gray scale cameras. By gray scale, it is meant that the 1,024 Pixel array cameras can measure the intensity of light being reflected from an object in 256 gradients of reflectivity, ranging from white to black.

As lumber is conveyed beneath the scanning system, neon lamp banks are alternately strobing at approximately 220 cycles per second. By evaluating the difference in light intensity reflected to the cameras from each lamp, the system can accurately determine the slope of the surface being measured.

Thickness information gathered by the profile calibration lasers is linearly interpolated with optical data on the slope of the surface, enabling the system to generate profile information every .120 inches along the length of the board. Eighty, five-point profiles are saved on the maximum length board. These 80 profiles can be placed virtually anywhere along the length of the board.

In the case of the trimmer, the .120 inch length measurement accuracy provided by the system eliminates the need for lumber to be accurately even-ended prior to scanning, and is the key to accurately positioning lumber longitudinally with the high resolution movable fence. A thickness measurement is taken every .0160 inches across the width of a board, at up to eight locations along the length of the board.

All of this data is then relayed to the optimization sub-system, which, as described earlier, analyzes the data and arrives at an optimum decision.

The system database includes an eight species product assortment file. Species or categories can be used to differentiate lumber species or specialty items. The system can be driven by volume considerations or price.

Each species, or category, can contain:

- 16 lengths.
- 16 widths.
- Chip value.
- 8 thickness categories.

Each thickness category can contain:

- Four grades or wane allowance tables (% face, % depth, and % length wane).
- Thickness control code, minimum and maximum target sizes.
- Split or multiple board charges.
- Assortment tables specifying lumber products by width, length, quality and value.

All data base parameters may be easily modified by the user through the graphics terminal.

Some of the other utilities of the system include a price matrix report which allows system performance and operation to be controlled or modified by adjusting production variables such as price and wane rules. Also, a shift report is generated at the end of each shift. An up-to-the-minute report can be called up at any time during a shift.

System performance and accuracy can be monitored with board plots on the graphics terminal. Board data can be saved in this form on floppy disk and replayed off-line using different parameters and prices. This not only allows the system to be tuned with running but a few boards, it also provides mill management with the capability to evaluate the possible effects of mill performance on price or parameter changes before a board is even run.

Summary

I have outlined how each of the sub-systems work together as a system to accomplish automated, value driven processing decisions based on precise three dimensional measurement of lumber.

At this point, I would like to introduce what we have chosen to label the "Q-Option" (see Figure 1, plate 4).

Earlier I explained how cameras, in conjunction with alternately strobing lamp banks, were used to record differences in reflectivity from the surface of a board. Together with thickness information from the profile calibration lasers, this optical data was interpolated to generate profile information on the board.

Waney edges, because of their relative changes in slope, are not the only characteristics that cause differences in reflectivity from the surface of a board. Usually, the great majority of the surface area of the board is relatively flat. Within that flat surface, differences in reflectivity can be caused by knots, splits, cracks, grain, pitch, stain, etc.

With the "Q-Option", when we are detecting and analyzing difference in reflectivity **between** points on the surface of the board to extract information on recognizable defects. With profile scanning we are detecting and interpolating relative differences in refectivity **within** specific points on the surface of the board to record information on board profile.

The "Q-Option", when extracting grade information, uses the basic camera system that is presently used strictly for measuring the boards geometrically. The large amount of data from the camera system is electronically reduced on an interface card without losing important information about the defects. The system automatically adapts itself to dark or bright boards.

The size and position of every defect is saved in the memory to be used in grading calculations. The grading rules are a set of software parameters, adjustable by the customer. The information about the grade and the geometrical measurements is used to find the most valuable board alternative, according to the price list input from the customer.

One company in Scandinavia has installed three "Q-Options" to existing SAAB edger optimizers. When adding defect information to existing profile information, tests showed an average increase of 3.8 percent in grade recovery. As a result of these tests, the same company recently ordered four more "Q-Options" to upgrade their remaining edger optimizers. Additionally, three other companies have ordered a total of six "Q-Options".

We hope to one day develop the logic to modify the software to implement the "Q-Option" here in North America.

Trimmer Optimizer Measurement Techniques

F.G. Bear Tinsley, AccuRay Corporation, Portland, OR

This paper explores the current stage of development of green trimmer optimizer systems (Figure 1) and their associated measurement, processing and control technologies. It further presents evidence to support the performance advantages of thickness and profiling measurement technology offered by AccuRay Corporation, although this so called "mechanical contacting" technology can have a very negative psychological impact on potential end users if not carefully evaluated.

AccuRay Corporation is a Columbus, Ohio based process control system manufacturer serving primarily the forest products industry. Total sales revenue in 1983 exceeded 116,000,000 $US and employment worldwide is approximately 1,800. About half of these employees are located in the 60 countries worldwide where AccuRay products and services are sold. The other half are factory based. AccuRay has targeted the sawmill industry as a key business segment with plans for it to provide 25 percent of annual revenues by 1988.

Entry into solid wood measurement and control systems began as a joint development project with Weyerhaeuser Corporation in 1976. As of the end of March, 1984, more than 50 unit process control centers had been sold and installed. Twenty AccuRay trimmer optimizer systems are now installed with 12 additional units on order. To the best of our knowledge, AccuRay installed the first trimmer optimizer in the world. This was at Weyerhaeuser, Everett, Washington, in early 1979.

Key criteria in the design and development of AccuRay sensor and system technology for green trimmer applications was priorized as follows:

- Precision - Trim decision accuracy will be no better than the quality of measurement.

- Proven Technology - Development must be in-house not at the customer's sawmill and at his expense.

- Maintainability with the average level of expertise found in the sawmill. Customer should not require a costly specialist.

- Ability to measure wane up or wane down. True automation and optimum economic return mandate this.

- Configurable cut logic. Ever changing market conditions mandate "user friendly" modification of cut logic parameters.

Virtually all potential measurement techniques for thickness, width, length, wane and end defects were explored. These included pneumatic, proximity, nucleonic, sonic, optical, laser and mechanical approaches.

We at AccuRay recognize a tendency for products to be technology driven by the incredible advances in technology over relatively short time periods. Strict discipline must be maintained toward design of a system architecture that will provide a more or less generic product versus a custom design for every application. We refer to this as "Evergreen Technology". Long-term hardware, software, system expansion and service support mandate this.

In the venacular of Star Trek a "deutronium plated, di-lithium crystal powered, photon modulated warp drive impulse power system" may be exactly what Scotty and Dr. Spock need for interstellar travel, but may not have application in the sawmill, particularly if the design cannot be maintained from a cost or manpower standpoint.

Each and every AccuRay trimmer optimizer installation has been an unqualified success with fast startups, immediate economic benefits and extremely high system reliability. This aspect of the product pleases us most and differentiates AccuRay from the often long and complicated startups of other vendor offerings. We believe the 6000 Green Trimmer Optimizer means the difference between just some results and optimum results!

The majority of lumber manufacturers we have spoken with over the past few months believe that their market conditions have permanently changed. They see optimization of bucking, primary breakdown, edging, cant and trimming as essential to their long-term survival.

We offer the strong demand for our product, in the midst of an industry recession, as evidence that this is indeed true. I believe it is fair to say that process control is no longer optional in the sawmill.

What is happening at AccuRay? We are continuing to perfect our existing products, particularly the trimmer and primary breakdown control systems. Concurrently, we are investing heavily in development of new and advanced systems with the aim of being the lowest cost, highest quality supplier. Our eventual goal is total control of the sawmill.

Product enhancements in terms of higher lug rate, increased capacity for thickness-width combinations and improved measurement accuracy have added significantly to system performance and application. AccuRay's 6000 trimmer optimizer will process boards wane up or wane down at 90 lugs per minute. Unlike the problems normally associated with optical measurements, the thickness profiling measurement approach utilized in AccuRay's optimizer is unaffected by variations in grain density, moisture, surface smoothness, color, ambient light and camera dynamics. Resulting accuracies are as follows:

- thickness: .010" (.25mm)
- width: .060" (1.5mm)
- length: .400" (10.2mm)

In addition to the high degree of accuracy and reliability achieved, AccuRay's profiling/thickness measurement is virtually indestructible; so much so, that the sensor is guaranteed for five years against failure. The 6000 System is warranteed for one full year against failure and all continuing parts supplied carry a similar guarantee.

The option of utlizing an IBM PC XT computer for single trimmer optimizer applications, as opposed to our multi-process Sawmill Information System, has brought the 6000 product within the reach of many additional sawmills producing 25 MMBF, or even less in some cases. Data base information is identical and allows you to structure your own customized management information system with "off the shelf" software.

Product design and application expertise combines to reduce overtrim to less than one percent in a typical application without sacrificing undertrim. Range of economic improvement has been from $10-24/MFB with $18 MFB as an average. These benefits have proven to be sustainable over the long term. If you are "strapped for cash" AccuRay's production rental program will help you to optimize without a sharp capital bite.

Generally, an AccuRay trimmer optimizer can be installed with minimal changes to the manual trimming operation. Startup time is a few days and the system yields immediate improvement in monthly cash flow. The system is designed to be maintained by the average sawmill technician or electrician.

We believe the trimmer is the best place to begin with optimization and will yield the best return in the shortest period of time. Since, in most cases, all of the mill production exits through the trimmer the AccuRay 6000 can act as qualifier and quantifier for optimization of, or adjustments to, other upstream process control centers. The trimmer optimizer in addition to yielding tremendous economic benefits can also be a powerful production management tool.

Application Review

Before investigating measurement requirements for a trimmer optimizer system I will review a few application considerations. According to Ed Williston, dean of sawmill consultants, the primary function of the sawmill trimmer should be to remove feather ends (interior waney areas), spear ends, and roundbacks. In other words, trimming in the small log sawmill should be confined to removal of bad ends, and excess wane on the ends or in the interior of a piece of lumber. The need for optimizing at the trimmer is due to grading rules for dimension lumber.

The trimmer operator needs to consistently maximize wane, within the grading rules, in order to offset the rapidly rising cost of wood--i.e., maximize lumber recovery. All this is a round about way of saying we're trying to reduce overtrim and undertrim. That is where the primary economics are in a trimming operation. Potential for improved prime length recovery and piece rate increases is also substantial.

The complexity of the grading rules make the trimmer operator's task especially difficult considering lumber is moving past him at 35-90 pieces per minute. This forces conservative decisions which waste wood and lower the lumber recovery factor. It is beyond human capability to judge wane to the fraction of an inch that is required by the grading rules.

The grader (trimmer operator) is therefore forced to be conservative (in order not to overload the planing mill, among other reasons) and overtrim, when in doubt about the width or length of the wane on a board. If the operator is liberal in his interpretation of the wane rules, he undertrims and can severely overload the planing mill.

Not all trimmers, nor all lumber products, lend themselves to optimization. Small log dimensioned operations generally offer the greatest return on investment. Some definitions:

Small Log Mill

The definition of a small log mill varies as to the location. Small log mills in the South will be different from small log mills in the Pacific Northwest. Ed Williston has seen fit to define a small log as four to 20 inches in diameter, inside the bark at the small end. Log diameter is important only because the smaller the log the more wane on the lumber cut from it.

The larger the log the less wane exists on a percentage of lumber basis. This should be pretty obvious. The AccuRay 6000 micro trimmer optimizer is designed to measure the wane on lumber, in effect the surface geometry of the lumber, and determine if it passes or fails the grade criteria (wane rules) the mill plugs into the system for a given species.

Large Log Mill

These types of mills are found predominantly in the Pacific Northwest, California and parts of British Columbia. They normally utilize old growth or virgin timber as all or part of their log source. These mills normally make the higher grade, higher value lumber, although they will produce some dimension lumber from those boards cut from near the perimeter of the log, and the smaller logs they cut from a given stand of timber. Much of the South's timber is plantation grown and much more uniform in size than timber in the Pacific Northwest.

Usually the percentage of dimension lumber is small compared to the percentage of higher value lumber. This higher value lumber is graded according to different rules as compared to dimension lumber. As an example, in a large log mill that is 30 percent dimension and 70 percent higher value product, the higher value material is graded to visual grade rules rather than "surface geometry", or dimension lumber rules.

This is normally not a good application for a trimmer optimizer as a trimmer operator is required to input grade rules for this higher value lumber. Consequently, the economic justification to the mill for a trimmer optimizer must now be based on the 30 percent dimension lumber produced rather than on the entire mill output.

Dimension Lumber

Defined as lumber with a nominal thickness of from two up to, but not including, five inches with a nominal width of two inches or more. Dimension lumber is designed for use as framing members for housing or light industrial construction, usually including studs and possibly boards, and is essentially a lower grade material simply because of the amount of wane allowed on the lumber. Boards are defined as one inch nominal lumber.

Dimension lumber, therefore, is almost by definition small log lumber. It makes little sense to make dimension lumber, with its loose grading rules, out of large logs with their corresponding greater percentage of "square" lumber. The higher quality lumber (the selects, shop, clears, export, etc.) is normally cut from the larger logs because there is a much greater portion of "square" lumber in a large log (lumber with no wane).

Wane

Wane occurs where the edge of a board contacts the outside of the log, i.e., where the log has curvature. Small logs will therefore make boards with a much higher percentage of wane than will large logs because of the relationship between the surface area to volume of a cylinder.

Remember that the purpose of the trimmer optimizer is to remove as much wane as is necessary to meet the appropriate grading rules. We are trying to detect thickness or shape variation (surface geometry) in order to grade the lumber coming through the trimmer. This should help explain why most dimension lumber is made in small log mills rather than in large log mills.

Multi-drop Trimmer

No explanation should be necessary, other than to state that the multi-drop trimmers are predominant. "two-saw", "mountain", or Canadian trimmers, although within the measurement and control capability of the AccuRay system, are generally not practical applications. This is due to the lack of available mechanisms to handle high speed piece rates and extensive positioning of boards (8-12 feet).

Surveys we have run indicate that two-saw trimmers represent less than 25 percent of the systems in the industry. We are seeing a definite trend away from the two-saw and back towards the multi-drop system. Superficially, it would appear that a multi-drop conversion is less costly than the mechanism to handle extensive board positioning.

Species

The number of species processed is important from the standpoint that capability of running multiple species through the trimmer optimizer with their corresponding different grading rules exists only so long as they are not run at the same time. Different species of lumber have different grading rules, even if they are all used as dimension lumber. You can mix species in a trimmer optimizer as long as you are willing to use the same grading rule for the entire mix.

Systems are not yet smart enough to differentiate between species and apply the different grading rules to the lumber as it passes through the trimmer optimizer. You can only run one set of grading rules at a time, unless you are willing to differentiate by size or trust the operator for a manual input on each piece. That is, if all 2x4's were of one species and all 2x6's were another, you could apply the different grading rules by size. Normally, however, one would not have that luxury in a mill.

Lug Speed, Lug Spacing, Lug Coverage, Board Width, Length and Thickness

All are interrelated, and it is important that these parameters are understood to properly apply an optimizer. The AccuRay trimmer optimizer is capable of running at 90 lugs/minute with boards 12 inches wide or less and with a lug spacing of 28 inches or more. This is with lumber that is 32 feet or less in length. When you increase the board width, effective lug rate is decreased and lug spacing requirements increase. When we talk about board width and length, you must realize that we are referring to the widest board and the longest board that the system will see.

Accuracy Lumber Profile Sensor

The thickness sensor is an injection moulded nylon arm attached to an 8,000 counts per revolution digital shaft position encoder. The nylon arm has two carbide reinforced points which alternately contact the board. The short point measures the leading edge wane, while the long point measures the trailing edge wane. The digital shaft position encoder measures the angle of the arm. The location of the tips of the arm can be determined by simple trigonometric relationships. Physical relationships determine when the tips are contacting the board, consequently the thickness profile can be generated.

Measurement Principles

At each measurement cross section there is both a top and bottom arm. Only the operation of the top arm is described here; the operation of the bottom arm is essentially identical.

The other, secondary, components of the sensor are a heavy duty bearing assembly, a spring to maintain arm contact with the board, and a shock absorber to minimize arm bounce. The thickness sensors are located on two foot centers with sensors both above and below the board. One foot spacing is available as an option, however, repeated studies have proven that 98 percent or more of manual overtrim can be eliminated with two foot spacing and extrapolation of information between sensors.

The width, length, end defect, and location of the ends of the board are measured by a light curtain and photo diode arrays. The photo diodes are at 0.2 inch spacing, however, they are only sampled every 0.4 inch for length, position, and end defect purposes. They are sampled every foot for width purposes.

Measurement sampling is synchronized with chain movement. The thickness sensors are sampled every 0.125 inch of chain travel. The widths are sampled every .060 inch. Length, position, and end defect are sampled every 0.4 inch.

Measurement Principles

One of the basic principles of statistics is that the standard deviation of the measurement must always be equal to, or greater than, the measurement resolution.

The resolution of the original thickness sensor was 0.007 inch for the short point on a four inch board, which was quite good. The resolution of the long point was 0.011 inch. The resolution improved for thinner boards. AccuRay has traditionally quoted a thickness accuracy of .020 inches though substantially better accuracies have been achieved. Recent system enhancements have resulted in improvement to better than .010 inches. Since samples are taken every 0.1. inch, the resolution of the width measurement is 0.1 inch. This is presently being enhanced to .060 inches.

We are often criticized for our "mechanical/contacting technology" and asked why laser or other optical technology is not utilized. Although we are seeing significant improvement in the quality and reliability of lasers, we do not yet believe they represent a practical, reliable and accurate approach to trimmer optimizers for thickness, length or profile.

Our own experience with laser based measurement for sizing control, we refer to it as a Lumber Measurement Module (LMM), more or less confirmed our original expectations. Variables such as color, grain density, moisture, smoothness and others that affected reflective characteristics yielded unpredictable and unacceptable results.

Reliability and accuracy problems caused us to eliminate this product as part of our offering during prototype evaluations. As further evidence in support of our conviction we have successfully replaced a competitive optically based system at a cedar mill in North Vancouver, B.C.

In order to get the best leading and trailing edge measurements, the short point data is used until the long point lifts the short point off of the board. The data is then taken from the long point until the trailing edge of the board is detected.

The input from each arm is a pair of pulse trains that are counted by a pulse rate counter. One pulse train is out of phase with the other. The counter counts up if the first pulse train leads the second, and down if the second pulse train leads the first. In this manner, the pulse counter content directly represents the arm angle.

Critical Dimensions of Profile Arms

As shown in Figure 2, too long an arm cannot contact and thus cannot accurately sense leading edge wane. Also, too short an arm cannot contact and thus accurately sense trailing edge wane, as shown in Figure 3.

To ensure that the arm tip will follow a sufficient leading wane angle (L_{max}), its angle as measured down from the horizontal (see Figure 1) cannot exceed the desired wane angle when the arm just reaches the top of the board. The equations governing the arm geometry for leading edge wane are as follows (see Figure 4):

L_{max} = arcsine(1 - (H + T)/R)

R = (H + T)/(1 - sine(L_{max}))

Where:

R = Arm radius
H = Distance of arm tip below board passline
T = Thickness of the board
L_{max} = maximum measureable angle of leading edge wane

To insure that the arm tip will follow a sufficient trailing wane angle (T_{max}), the sum of the desired wane angle and the arm angle needs to be less than 90 degrees. The equations governing the arm geometry for trailing edge wane are as follows (see Figure 3):

T_{max} = arccosine(1 -H/R)
R = H/(1 - cosine(T_{max}))

Where:

R = Arm radius
H = Distance of arm tip below board passline
T_{max} = maximum measureable angle of trailing edge wane.

No single arm of any practical dimension can satisfy the conditions necessary to properly measure both leading and trailing edge wane. However, by having two points on the arm, one short and the other long, a good leading and trailing edge wane measurement can be obtained, see Figure 5. An arm was developed with a short point radius of R_1 to follow the leading edge of the board, and a long point radius of R_2 to follow the trailing edge of the board. Leading and trailing wane angles of better than 60 degrees can be accurately measured by this arm.

The trailing edge of the board is detected by limit checking the angular acceleration of the arm; the arm accelerates rapidly once it falls off the edge of the board. If the wane on the trailing edge is steep enough, the bottom and top contours will not have the same number of points, due to one arm falling off the board before the other. When this happens, the contour with fewer points is extrapolated at a fixed slope until the arrays are the same length.

Measurement Processing

The measurement processing for the top and bottom arms is essentially identical, so only the top arm will be discussed. The thickness measured by both the top and bottom arms are referenced to the same imaginary line below the passline (top surface of the chain rail) as shown in Figure 6.

The counter content is sampled every 0.067 inch of chain travel. When the arm's short point is exactly vertical, the translation (board movement) variable X0 is initialized to 0. X0 is then incremented for each sample. By subtracting the horizontal position of the short and long arm points (XS and XL) from X0 each time a sample is taken, the board is made to appear to "stand still". XS and XL are in units of sample counts. The translated (or stationary) points are:

XSS = X0 - XS
XLS = X0 - XL

In Figure 7, XSS is negative until the short point is over the leading edge of the board. When XSS is positive, the thickness values (YS) are stored in the contour array at the location corresponding to XSS. When the long point comes over the board (becomes positive), each long point thickness value is compared with the appropriate short point thickness value, to determine where the short point is lifted off the board (circled in Figure 6). Starting at this point, and running until the arm leaves the trailing edge of the board, the thickness value (YL) is used for the board contour.

The location of the tips of the arm can be determined by simple trigonometric relationships. The resolution of location of the ends of the board is 0.4 inches which is more than adequate for length and defects.

Cut Logic Comments

Based on the results of several studies, an operator attempting to load all pieces wane up will load approximately five percent with the wane down. A wane up only system will make an incorrect decision on most of these pieces. This can result in five percent loss in economics. Even though most of the incorrect decisions result in undertrim, it is an easily demonstrated fact that most undertrim decisions ultimately result in overtrim also. Since the AccuRay trimmer operates in both the wane up and down modes, full economics are assured.

The system supports 40 thickness by width combinations. Since the thickness and width limits are not independent they are applied as a pair to evaluate the product the mill was attempting to make. This eliminates the risk of applying thickness limits for one product and width limits for another.

Once the excess wood is determined, the trim is biased toward the end with the lowest confidence in the good wood boundary. We believe this is a good approach. In other words, 25 percent is taken off the highest confidence good wood end and 75 percent from the lowest confidence end. This strategy helps to avoid underlength pieces in the planer mill.

The cut logic takes into account all of the following parameters:

- Too thick.
- Too thin.
- Marginally too thick for too long a section.
- Insufficient sawn and planed face.
- Too wide.
- Too narrow.
- Marginally too wide for too long a section.
- Insufficient sawn and planed edge.

L_{max} = arcsine(1 - (H + T)/R)

R = (H + T)/(1 - sine(L_{max}))

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- Too narrow.
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- Insufficient sawn and planed edge.

We believe that this is a very comprehensive set of cut logic parameters (see Table 1).

The system has two computing levels in its architecture:

- The management information and support level can be either a Honeywell Level six minicomputer or an IBM PC XT.
- The measurement and control level is based on AccuRay's proprietary programmable micro computers (PMM's). These are 8080/8085 based microcomputers and their associated input/output support circuit boards. This level presently uses five of these PMM's, one for cut logic and overall control, another for photo diode array sensor processing, and three for thickness sensor processing. This is an excellent architecture, that provides for continued system expansion and enhancement.

The system specification is 90 lugs per minute. Width accuracy is .060 inches, length .400 inches and thickness better than .010 inches. Wane angles on both the leading and trailing edge can be physically measured to better than 60 degrees, and inferred at greater angles.

After installation, AccuRay offers a full range of service from resident to on-call assistance. A major industry complaint is the lack of and quality of follow-up services of process control suppliers.

AccuRay has been in the process control business for 30 years, and process control is our only business. We are large enough, and have sufficient industry diversification, to sustain short-term industry slow downs. This must be a key consideration when the lumber recovery potential is clearly understood.

We provide a comprehensive set of on-site and off-site training programs, including off-site "hands on" training laboratories. We guarantee a maximum five day installation and can count on our resources of 1,800 people.

Conclusion

We at AccuRay are delighted with the quality of our trimmer optimizer product offering. We believe we have demonstrated the soundness of our measurement technique and our overall market approach. It is our sincere hope that this paper has contributed to the understanding of trimmer optimizer applications. Each of our 20 installations (see Table 2) is an unqualified success. This paper was not prepared to slander optics, laser technologies or our competitors, but to examine practical application considerations and to support the contention that not all designs have to be technologically complex to be successful.

Table 1

Trimmer optimizer decisions

Green target size evaluation
(User programmed/volume or value)

Green target size equals
sum of dry size + allowance for:

A. Shrinkage

B. Planer allowance (Min. + Max.)

C. Allowance for sawing variation

D. Grade objective (nailing edge)

- Size parameters + value tables are user entered and are mill specific depending on cut objectives.

Sequence of cut logic
(20 thickness X width categories)

1. Nominal thickness + width deter.
2. Pass #1 (2 + BTR grade) = $0.00
3. Pass #2 (3 + BTR grade) = $0.00
4. Pass #3 (1st reman pass) = $0.00
5. Pass #4 (2nd reman pass) = $0.00
6. Software options:

   A. Trim save = Acceptable minimum length (8") returned for reman.

   B. Board split = Up to 8 split combination where long piece is cut back to make two shorter pieces of a combined higher value.

   C. Alternate grade = Operator activated allows system to evaluate pieces of different TXW + GRADE REQUIRED
   EXAM: #1 DENSE or "CLEARS"

Table 2

Results of AccuRay trimmer optimizers

Site	MBF/ Year	1982 Uptime	Improvement OT (%)	Improvement UT (%)	OT + UT Total ($)	*Prime Length ($)	Production	Additional Savings	Total ($/yr)
A	60,000	99+%	3.7	7.5	643,000	N/A	+12%	196,000	839,000
B	60,000	99%	3.5	6.4	474,000	120,000	+16%	58,000	652,000
C	70,000	99%	3.8	7.1	579,000	147,000	+14%	58,000	784,000
D	60,000	99%	14.0	1.3	935,000	N/A	+9%	-	935,000
E	60,000	99%	12.8	2.4	850,000	N/A	+9%	-	850,000
F	50,000	99%	13.7	5.6	1,442,000	N/A	+12%	128,000	1,570,000
G	50,000	99%	4.1	2.4	568,000	N/A	+12%	103,000	671,000
H	50,000	99%	5.6	3.2	620,000	320,000	N/A	100,000	1,040,000
I	55,000	99%	8.2	4.5	1,148,000	516,000	N/A	115,000	1,779,000
J	70,000	98%	-	-	-	N/A	N/A	-	1,000,000
K	105,000	99+%	4.0	(1.4)	1,115,000	N/A	+10%	82,000	1,197,000
L	70,000	99+%	4.1	0	629,800	180,000	N/A	186,000	995,800
M	35,000	100%	4.8	2.3	346,350	0	+24%	30,000	3763500

*Estimate

NOTE: All dollar values are based on AccuRay calculations using the 1982 industry average values for lumber, chip prices, labor rates, etc.

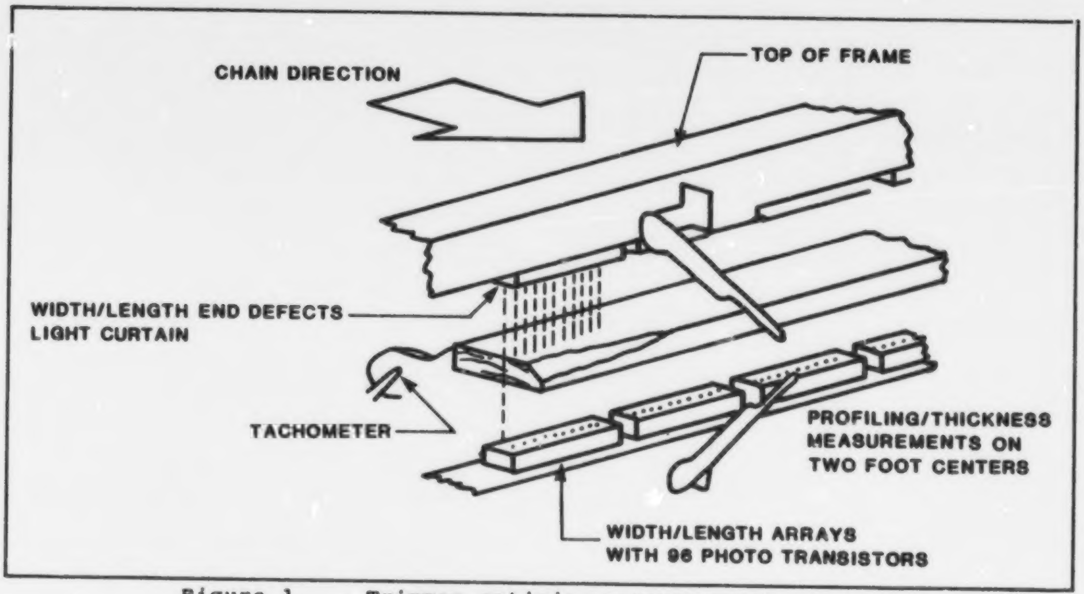
CHAIN DIRECTION
TOP OF FRAME
WIDTH/LENGTH END DEFECTS LIGHT CURTAIN
TACHOMETER
PROFILING/THICKNESS MEASUREMENTS ON TWO FOOT CENTERS
WIDTH/LENGTH ARRAYS WITH 96 PHOTO TRANSISTORS

Figure 1. Trimmer optimizer measurement system

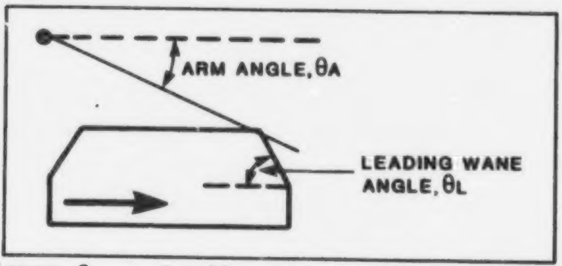
ARM ANGLE, θ_A
LEADING WANE ANGLE, θ_L

Figure 2. Leading wane versus arm angle

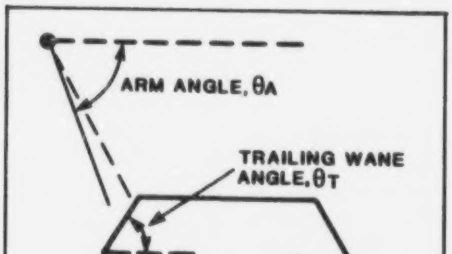
ARM ANGLE, θ_A
TRAILING WANE ANGLE, θ_T

Figure 3. Trailing wane versus arm angle

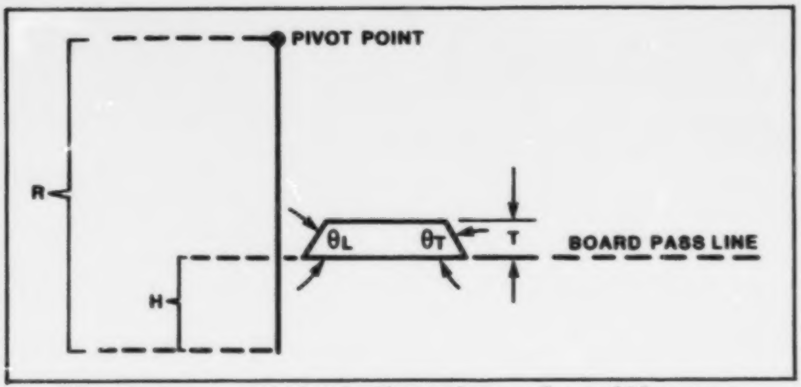
PIVOT POINT
R
H
θL
θT
T
BOARD PASS LINE

Figure 4. Critical dimensions of profile arms

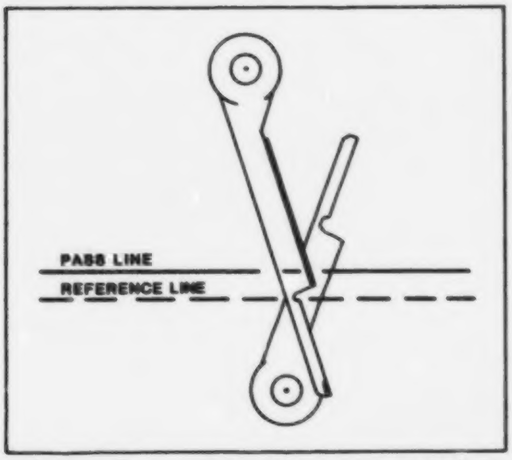
PASS LINE
REFERENCE LINE

Figure 5. Two-step arm geometry

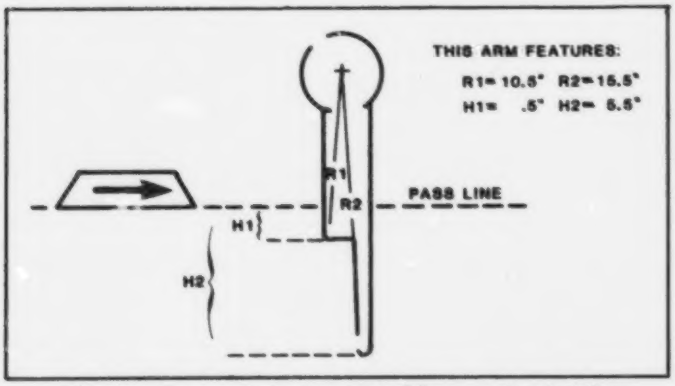
THIS ARM FEATURES:
R1= 10.5" R2=15.5"
H1= .5" H2= 5.5"
R1
R2
PASS LINE
H1
H2

Figure 6. Arm to passline orientation

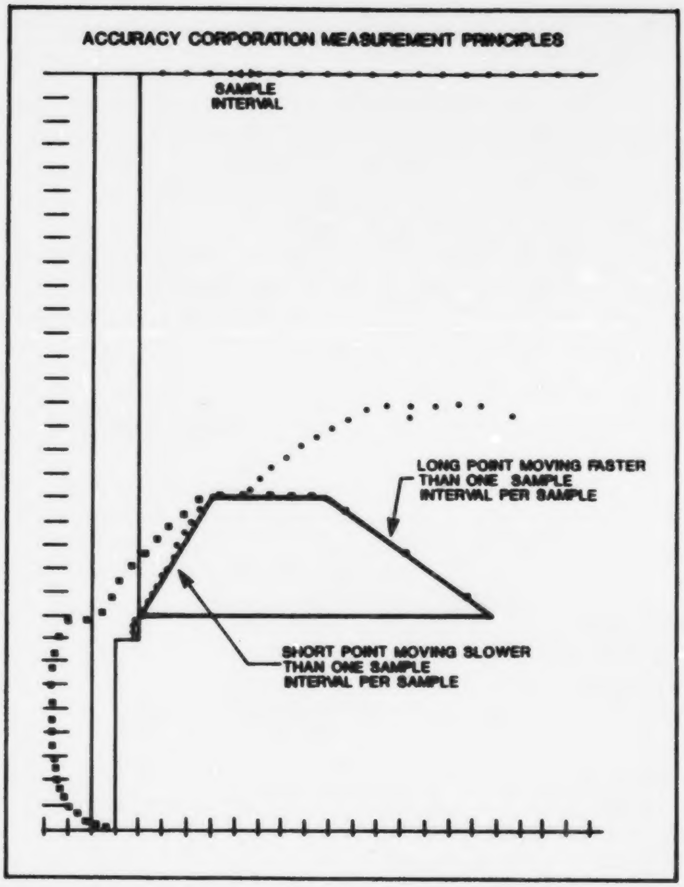
ACCURACY CORPORATION MEASUREMENT PRINCIPLES
SAMPLE INTERVAL
LONG POINT MOVING FASTER THAN ONE SAMPLE INTERVAL PER SAMPLE
SHORT POINT MOVING SLOWER THAN ONE SAMPLE INTERVAL PER SAMPLE

Figure 7. Conversion of samples to board contour

Primary Breakdown Measurement System

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This paper examines the task of converting cut-to-length logs into saleable lumber. The conversion of logs into lumber by a sawyer is the function of a keen eye, a knowledge of the market, and what the optimum yield out of every log is. His goal is to then determine what are the best products to target as an end result. This is difficult for the human eye to do for any given log let alone hour after hour and day after day.

I will review what is required in determining how a log could and should be broken down. I will deal with a variety of options and parameters that yield solutions to the breakdown challenge.

We must keep in mind that our goal is to make our measurement system as accurate as possible, so our model duplicates the form of the log. The objective then is to issue sets to control the primary breakdown equipment for optimum recovery. Our result is the most effective implementation of a reliable easy to use system for true optimization.

Dimensioning

In trying to represent a log in the terms described above, the first thing that must happen is for the log to be scanned or viewed by the mechanism that inputs dimensional information into the system. There are multiple options available to derive that information from the log. A row of light sources with a corresponding row of photoelectric detectors is the most straightforward and easiest to understand. It utilizes the shadow effect of the log breaking the curtain of light generated by the light sources. This shadow is projected onto a corresponding row of photo detectors. The lack of light is translated into dimensional information depending on the number of sensors under the shadow.

Position can also be determined, depending on which of the detectors are in the shadowed area. Diameters along the length of the log are derived as the log is transported longitudinally past the sensors. This method is as practical as any in that the scanning method is straightforward and proven. (Figure 1).

Camera technology is also an alternative when ambient light, contrasts, environment considerations and variations in the reflective qualities of the log can be compensated for. What the camera does is differentiate between different shades of grey within and between each of its detectable zones. Once it determines the color of each zone, the analysis becomes similar to that of the photo detectors. A graphic representation of the information obtained by either device will look the same (Figure 2). There are a variety of other measurement techniques available that we wil not investigate here.

The measurement method I will focus on is the array of photo detectors that was discussed first. No matter which technology is used, the result of the view is a two-dimensional representation of the log. What is obtained is the overall length and a sampling of diameters along that length. From that information, the taper of the log can be determined.

One consideration that cannot be overlooked in taper is the potential for flare. If this practical characteristic is not taken into consideration, the calculated result derived from only one large end and one small end diameter with an interpolated taper, can attempt to make lengths of lumber out of nonexistent fiber (Figure 3).

The end result will be the recovery of shorter lengths of lumber that may not be saleable. The other more desirable implementation is the extrapolation of the real taper through the flared section (Figure 4).

There is one additional bit of information that can be helpful in getting the most out of a log and that is the ovality of the log. If a second view of the log is taken, normal to the first, a three-dimensional representation can be made to allow the calculations to consider any possible benefit that could be derived from the log being out of round. Ovality is a bit of a misnomer in that logs tend to take on more of an elliptical shape than a true oval so that must be considered in the way the shape is modeled.

It is relatively easy to see, however, that a log being modeled with two-dimensional data could either overestimate or underestimate the size of a log depending on whether it is scanned in the major or minor axis. This translates directly into material that is either being underutilized (Figures 5a and 5b) or overestimating the actual recoverable lumber (Figures 6a and 6b). In the overestimation category, the end result comes down to lumber of reduced dimensions as mentioned earlier or a lower grade lumber or both.

The next thing that must happen is that the information generated by the detectors be processed by a smoothing algorithm that gets rid of undesirable variations. The output yields a model of the log that is free from distortions such as limb stubs and mechanical damage.

This now gives you the basic information required to process the log through the primary breakdown algorithm. The next thing we would like to investigate is the breakdown challenge itself.

Breakdown Challenge

The primary and most fundamental definition of what we are trying to do in this segment of the solution is to convert basically round logs into rectangular logs. The first mathematical calculation that takes place is that of rectangles fitting into a circular cross section of one log diameter. This involves the fitting of rectangles into a circle with allowances for the kerfs of the saws being used.

One factor that should be considered is the flexibility of the system to allow the change or evaluation of different kerfs and the effect of sawing variation changes on the mills output. These can be valuable tools in the evaluation of modifications to the operating procedures and hardware of any site.

Once satisfied that all these things are done, the larger task is to fit a length of that rectangular cross section into the cylindrical form of the log. This is accomplished by doing the fit calculations at intervals along the log coinciding with the lengths of lumber that are acceptable to manufacture. The feature that makes that a challenge is the taper of the log being considered.

All this amounts to is thousands of calculations involving various diameters along the length of the log. Each calculation can then consider not ony what can fit into that circle but what lumber value the different breakdown solutions will yield. Value is becoming the predominant method of determining how best to determine the most desirable product for manufacture, rather than the previously popular volume calculations. These calculations have to be done for every log that is to pass through the breakdown equipment. As you might guess this is not a trivial task and takes a formidable amount of time and computer power to accomplish.

The most well known of these programs is the Best Opening Face (BOF) program generated by the UD Department of Agriculture, Forest Service, Forest Products Research Laboratory located in Madison, WI. The program is available upon request from Madison. Due to its popularity, we will use it as a basis for conversion on the overall task to be performed.

AccuRays's solution is not based on this program but all of the points derived from analysis of their solutions are pertinent. As you may already know, this program allows you to evaluate the solutions generated by a variety of sawing methods on a given log or set of logs. The solution takes into consideration the criteria presented to this point with the exception of ovality. Those parameters being diameter, taper and kerfs.

The BOF program has been implemented in a variety of ways with about as many modifications as implementations. The program itself does not actually issue sets but rather the result is the positioning of the opening face and a list of the subsequent lumber produced. From this information, set information can be derived for the machine on which it is to be applied.

The evaluations done by the Forest Products Research Laboratory consider logs from 8 to 20 feet in length with diameters from 4.6 to 20.5 inches with tapers of one to five inches over 16 feet and kerfs of 0.125 to 0.375 with sawing accuracies of 0.0 to 0.5 inches. In addition, the BOF solutions can break a log down using a cant breakdown or live sawn algorithm with centered or offset capability in either full or split taper. These will be covered in more detail later.

As mentioned, one of the items that BOF does not take into consideration is the effect of log ovality on the solution and ultimately on the recovery. We show this as a significant impact on the overall efficiency of breakdown. Over a variety of log samples with actual measurements, ovality can be shown to have an average of 1.5 percent uplift if it is being factored into the calculations. That figure is above any accidental recovery derived from the log being oval but broken down as if it were round. The variations for individual logs gives from zero percent additional recovery for round logs to 10 percent for logs with larger ratios of ovality.

The more accurately you can model the real log, the more likely you are to get the most out of your raw material. In consideration of that, the more parameters you can consider the more accurately you can model the log. That is where ovality can add another dimension to the process.

The type of breakdown that the log will be processed under also has an impact on the recovery that will be expected. Again the Forest Products Laboratory has done some research on this and offers us some insights on the breakdown being used.

Algorithm

The two forms of breaking down a log are live sawn or cant sawn. Cant sawing takes flitches off the sides in one plane and breaks down the cant with saw lines at a 90° angle relative to the side board saw lines (Figure 7). Live sawing gives you vertical saw lines throughout the entire log (Figure 8).

The studies done at the Forest Products Laboratory find it a fairly close race for the optimum pattern. The latest study shows a variation of the cant sawing solution to be ahead of the other patterns. That is a change from some earlier findings.

The variations on live sawing are the fact that the log can be placed in a split taper position where the bottom of both the small and large ends are resting on a plane with the vertical center line of the small and large ends both aligned with the center line of the transport. Alternately, full taper places one side of the outside diameter of both the small and large ends into a vertical plane parallel to but offset from the center line of the transport.

Additional variations allow for a flitch to be cut out of the center of the log or a saw line to be centered in the log or finally, a variable placement of saw lines, the latter yielding the optimum for live sawing solutions. This variable placement of saw lines dictates that the relative position of the saw to the center of the log can be shifted to yield the optimum solution.

In the cant sawing solution, more variables can be encountered. In addition to split taper, full taper and a centered or offset cant, the processing of the cant itself can be handled in the same number of ways. The cant may be processed split or full taper and with a moveable or fixed fence. The studies indicate that the split taper configuration of the log and the full taper of the cant breakdown with a variable fence yielding all around superior performance with the exception of a band of diameters in the middle that are best broken down with the variable live sawing solution. One of the considerations for live sawing being better is that you have to be able to use narrow short boards from edging.

In addition to all of the things evaluated, AccuRay's implementation considers the possibility of a recoverable spline in it's calculations for installations on equipment that utilizes that characteristic. There is also a difference in the way the two systems deal with taper. AccuRay's system allows six taper classes that are configurable to the type of logs being processed. The taper classes may be configured to focus on the actual tapers encountered at any given place or time. The dimensions may be as close together or as far apart as needed to cover the conditions at any site.

No matter what the sawing solution, it must take into consideration the machine centers downstream that will effect recovery. Any additional resaws, gang saws, and all the capabilities and ramifications of the edger and trimmer must be taken into consideration before a valid solution can be generated. With a lack of interrelationship between these devices, the primary breakdown has little chance of yielding lumber that can be in concert with your green target sizes.

Summary

The first thing that must be done on each log, is the scanning of the diameter at closely spaced intervals along the length. The overall length must also be determined to the next shortest useable length. A smoothing algorithm needs to then be applied to each log as it is presented to the primary breakdown system. The smoothing algorithm plays an important role in the system as it is the computer's model from which the ultimate solution is derived.

Next are the calculations that generate the optimum lumber pattern out of the log. These must be as practically applied as possible so as no attempt is made to get wood out of thin air. Finally the sets must be built and sent to the center for actual processing of the log. All of these factors have important implications on the difference between theoretical and actual recoveries that will be realized.

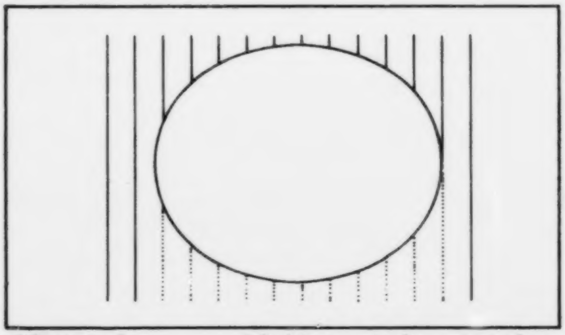


Figure 1. Light curtain scanning

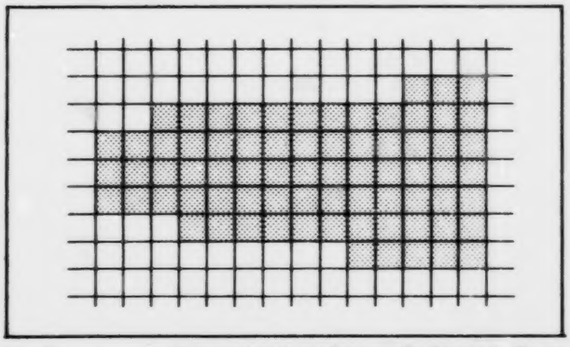


Figure 2. Representation of log information

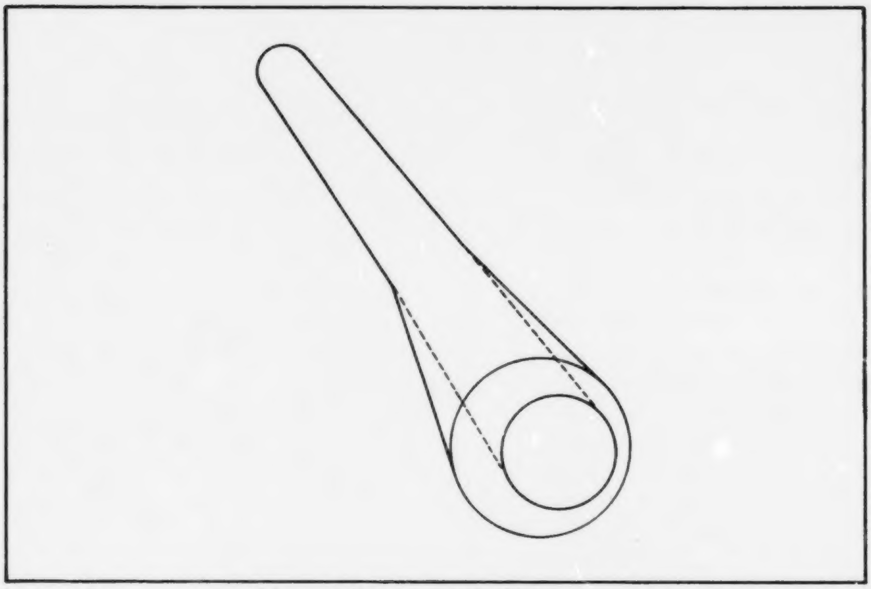


Figure 3. Small end/large end diameter taper interpolation

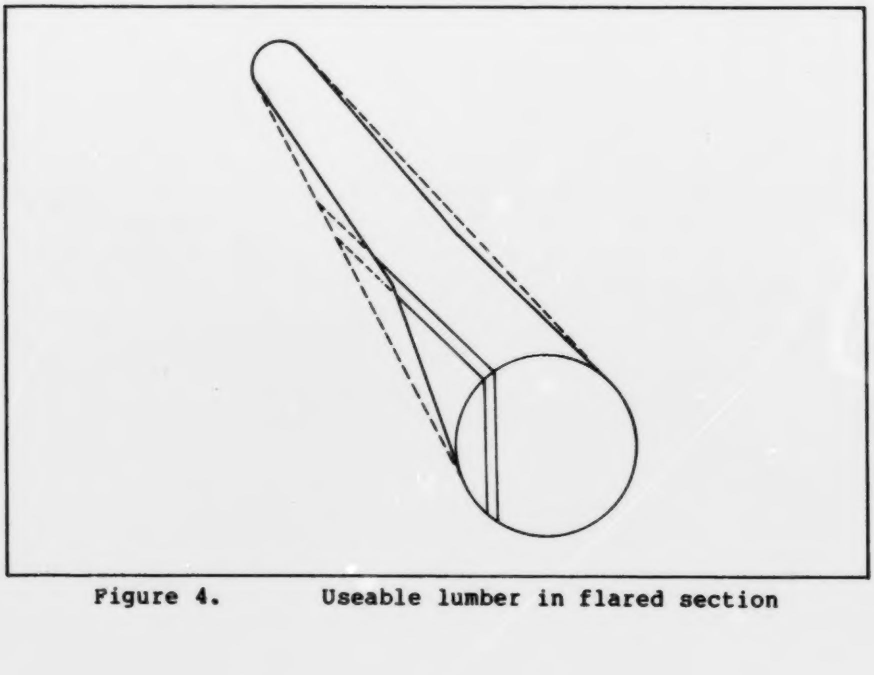
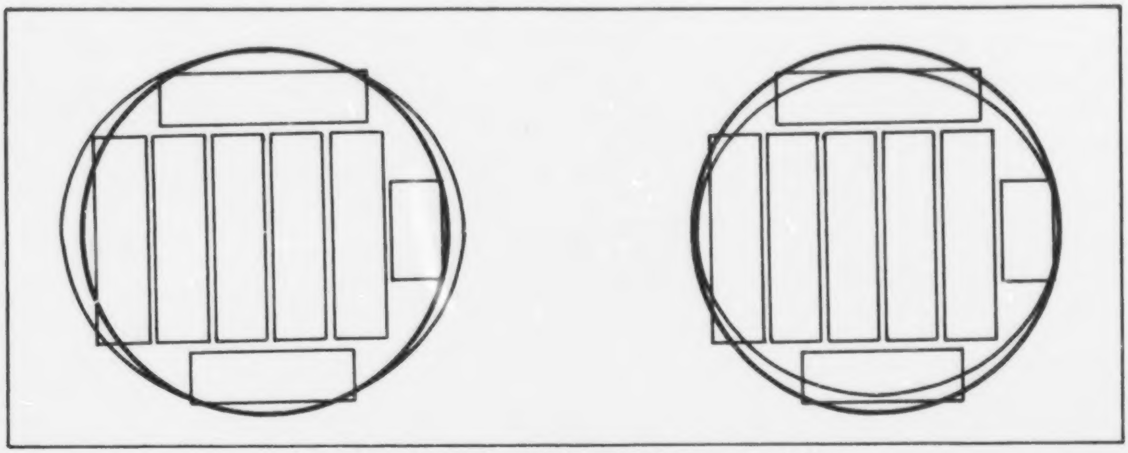
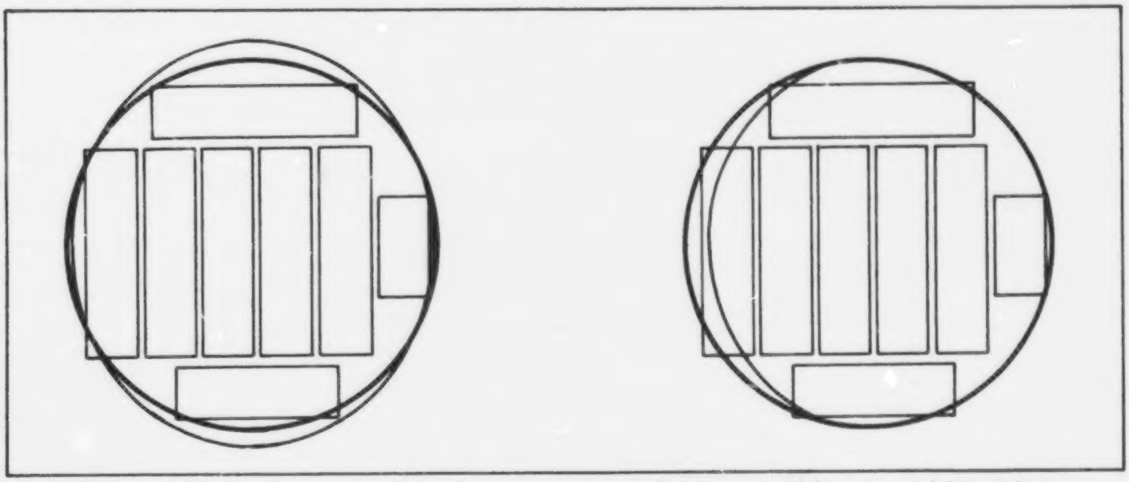


Figure 4. Useable lumber in flared section



Figures 5a & b. Underutilizing ovality



Figures 6a & b. Overestimating recovery without ovality considerations

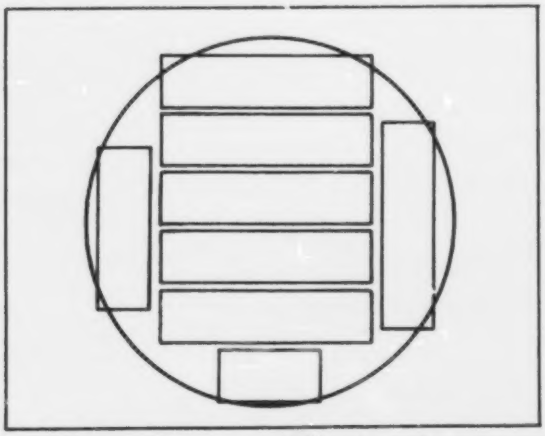


Figure 7. Offset cant sawn

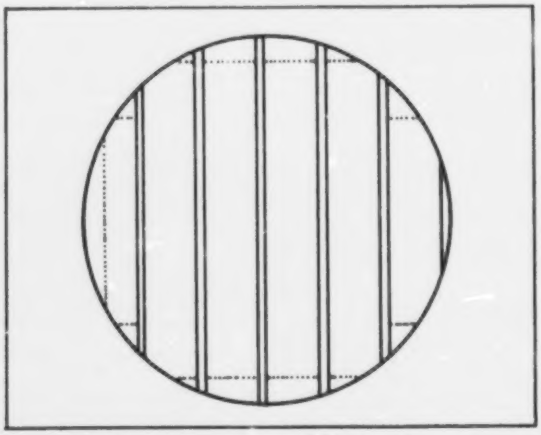


Figure 8. Offset live sawn

A Prototype Software System for Locating and Identifying Surface Defects in Wood*

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Continued increases in the cost of materials and labor make it imperative for furniture manufacturers to control costs by improving yield and increasing productivity. To address this problem the authors, in an earlier study, proposed an Automated Lumber Processing System (ALPS) that employs computer tomography, optical scanning technology, the calculation of an optimum cutting strategy, and a computer driven laser cutting device.

Of all the components of this system the one whose technical feasibility is most uncertain is the system for locating and identifying surface defects. In this paper, a prototype software system for performing these tasks is described. Further, this system is tested on 70 boards to determine the robustness of the algorithms. The results obtained are very encouraging but indicate more research is needed.

Introduction

When producing parts for furniture and other assembled wood products, logs (mainly hardwoods) are first sawn into different lumber grades with defects randomly located throughout the board. The defective lumber is then remanufactured into smaller parts and the defects removed by ripping and cross cutting. The process is labor intensive, and saw kerf losses alone waste substantial volumes of valuable lumber.

Conners et al. (in press) proposed, and attempted to show, the feasibility of an Automated Lumber Processing System (ALPS) for producing the same parts. In ALPS hardwood logs enter the process stream and are scanned by industrial photon tomography (IPT) to nondestructively locate internal knots and establish log geometry. Using this information, a optimum breakdown strategy is computed to maximize grade or value yield. The computer driven breakdown saw would then automatically saw the log into boards. Most boards, however, will still contain visible surface defects (i.e., knots, wane, stain, worm holes, checks), many of which cannot be detected using tomography.

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After drying and light surfacing, the boards are scanned on both surfaces using optical imaging devices. The resulting digital images are analyzed by the computer to identify types of surface defects and provide coordinate data on their location. The image derived defect data are then used to compute an optimum cutting pattern for each board, thus yielding the maximum number of parts for a given cutting bill.

In the envisioned ALPS process, parts are cut from the board using a numerically controlled, high-power laser directed by the computer-derived optimum cutting pattern. The primary advantage of laser cutting to this process is the small kerf (approximately 0.015 inch) and the ability to start and stop cutting at any location without having to cut all the way through the board, as is the case with rip and cross cut saws.

Lastly, parts are optically scanned for quality and sorted by size. Residue material is chipped and used for fuel.

Of all the components of the ALPS system the one whose technical feasibility is most in doubt is the system for automatically locating and identifying surface defects on the hardwood boards. The problem lies in the great variability of wood. No two boards have the same grain and each manifestation of a defect is different from any other. Consequently, a large part of Conner et al.'s work was devoted to demonstrating the technical feasibility of a system for locating and identifying defects.

Unfortunately, most such "laboratory studies" tend to be overly optimistic of the classification accuracies which can be actually obtained in practice. Hence, from a purely pragmatic point of view, it seemed advisable to develop a prototype system, one which could closely emulate the actual operational environment, to check the algorithms developed.

In what follows the prototype system will be described. Further, the results of the application of this system to 70 boards will be detailed. Finally, the conclusions which can be drawn from the study will be presented.

The Prototype System

The basic strategy used in the system is to divide the image of the board into a number of disjoint rectangles and classify each rectangle independently. This is illustrated in Figure 1. Part (a) of the figure shows how the image is divided and part (b) shows the desired output of the system. Using this type of a procedure has the advantage of allowing a straightforward parallel processing implementation. This is important since it is unlikely any one microprocessor could keep up with the processing requirements imposed in a commercially useful ALPS.

To further accelerate the analysis process a sequential classifier is used. The decision points of this classifier are shown in Figure 2. It is designed so that the more computationally complex measures need be evaluated only in those instances where it is absolutely necessary. In what follows each component of the prototype system will be described.

Differentiating Board from Background

It is assumed that, in the industrial environment, the tonal properties of the background upon which the board is placed can be controlled. Doing so allows one to use a simple thresholding method to differentiate board from background. In particular, in these experiments the background was black. A region was considered to be background if it contained more than a specified number of pixels below a threshold value. The objective is to claim a region is board if it contains "only" board.

Differentiating Clear Wood from a Potential Defect

The purpose of the Node 2 decision of the classifier, shown in Figure 2, is to distinguish a region which contains only clear wood from one which might potentially contain a defect. Because of the grades of lumber typically used in furniture manufacture the boards are guaranteed to be 80 percent or more clear wood.

Further, Conners *et al*. (in press), indicate that this differentiation could be made reliable by computationally simple measures, i.e., the mean, variance and skewness of the gray levels. On the other hand, the measures required to make the Node 3 decisions are computationally very complex. Hence, the purpose of this decision node is to help reduce the computational burden.

To make the first-order measures meaningful the same lighting conditions were used to scan the boards. Further, a simple shading correction was applied to each of the disjoint regions' gray levels before the mean, variance and skewness were computed. Note, both controlled lighting conditions and the necessary input to a shading corrector can be obtained by appropriately designing the ALPS.

The decision scheme used, $N(\vec{\mu}, \epsilon)$, assumes that the mean, variance and skewness measures are computed from regions containing only clear wood. Given a measurement vector the question addressed is whether, to a certain level of confidence, this vector is from the $N(\vec{\mu}, \epsilon)$ distribution. Under the normality assumption a standard Chi-squared test can be used (Morrison, 1967). In particular, a region is considered clear wood if its measurement vector x is such that

$$(\vec{x} - \vec{\mu})^t \epsilon^{-1} (\vec{x} - \vec{\mu}) \leq T.$$

otherwise the region is considered to contain a potential defect.

Differentiating the Types of Defects

Note that the Node 2 decision, differentiating clear wood from potential defect, relies only on tonal properties. To differentiate the type of defect present requires more than just tonal properties (Conners *et al*., in press), it also requires pattern related measures.

The pattern related measures used are ones defined off co-occurrence matrices (Haralick *et al*., 1973). An element of the cooccurrence matrix, δ,(S(δ, T) =

$[s(i,j,T)]$, is an estimate of the second-order probability of going from a pixel with gray level i to a pixel with gray level j given that the two pixels are $\delta = (\Delta x, \Delta y)$ units apart.

This estimate is computed over a region of size and shape defined by the tile T. It is usually convenient to refer to $\delta = (d, \theta)$ in its polar form, where $d = \max(\Delta x, \Delta y)$ and θ = arctar (x/y). The measures defined off the cooccurrence matrices used are the inertia, cluster shade, cluster prominence, energy, entrophy and local homogeneity. The definitions of these measures can be found (Conners *et al.*, in press).

The decision method used was a pairwise multi-class classification scheme. Using this procedure, the process for deciding in which of K possible classes a region belongs is broken into $\binom{K}{2} = K(K-1)/2$ classpair decisions. The result of each of these classpair decisions is tabulated and the region is considered a member of the class into which it was placed the most times.

It is assumed that each class-conditional density function is normal and the *a priori* probablities of the K classes are all equal. Each classpair decision is made using a Bayes method. The measures used to make each classpair decision were chosen using a forward sequential search measurement selection algorithm.

Experimental Methods and Results

The objective of the study was to determine how well the procedures described by Conners *et al.* would work in the industrial setting. To this end 70 boards, each approximately 15 inches in length and of varying widths, were selected as data. The desire was to approximate a group of boards that might be processed by a furniture manufacturer. All boards were Southern red oak since that was what was used by Conners *et al.*

The percentage of area containing a defect was restricted to about 80 percent of what one would expect from the grades of lumber typically used. Further, the types of defects present represent about 95 percent of what one would normally encounter in hardwoods. The defects considered were knots, holes, wane, stain, mineral streak, bark pockets, splits, checks, and stain.

A vidicon type scanner was used to digitize a section of each board. The optics were such that the 512 x 512 x 8-bit resolution was distributed over a 8 1/2 x 8 1/2 inch area, i.e., about 60 pixels per linear inch. Frequently during the scanning process a test image was scanned. This image was used to re-calibrate the shading corrector. This frequent re-calibration allows for possible drifts in either the light source or the vidicon tube.

Using these scanned images as data the prototype system would read each image and divide it into 64 disjoint regions each 64 x 64. Each of these square regions was input into the decision making logic described in the last section. A total of 1,326 regions containing board were processed. The rest were background regions eliminated at the first node of the processing.

Note, none of these regions were used to train the classification logic. Rather, the decision surfaces obtained by Conners *et al.* were used in this study. Consequently, each region considered was different from any that had ever been used to select the measures, or estimate means and covariance matrices.

The results obtained can best be explained in two steps. First, and most important from the research point of view, is considering the system performance on the two class problem, clear wood versus defect. The results of this two-class breakdown are given in Table 1. Note that there were 977 clear wood regions and 349 regions containing a defect; the ratio one would expect on the grades of lumber normally used. Next, note the approximately 95 percent correct classification rate.

What makes this classification rate particularly impressive is that it was obtained by the Node 2 decision logic. An examination of the results indicated that only one region was classified as clear wood by the Node 3 logic. Hence, this classification accuracy is obtainable using only the computationally inexpensive first-order measures mean, variance, skewness and, of course, the shading correction procedure.

The simplicity of these measures, the shading corrector, and the decision logic indicate that an implementation of this classification process can be easily achieved in such a fashion as to meet commercial speed requirements.

The next step in examining system performance is to determine the accuracy with which it can classify the type of defect present in a region, i.e., the robustness of the Node 3 procedures. The need to classify the type of defect present stems from the variety of uses of the wood parts manufactured. Some parts are used in forming visible surfaces such as table tops. Such parts must be defect free so that they will have a good visual appearance. Others, however, are used in invisible areas, i.e., in forming the frame of a piece.

In such instances all that is required of the part is that it be sound, i.e., capable of withstanding the forces normally imposed upon the frame. Thus, it must only be free of those defects which might affect its strength.

To address this need the system was formulated to consider a 10 class problem. The classes considered are clear wood, splits and checks, knots, decay, mineral streak, wane, holes, stain, dark bark, and light bark. Note the split and check defects were merged into one class because of their very similar visual appearance. Conversely, the bark pocket defect class was broken into two classes, light bark and dark bark, because of the visual dissimilarity of these two entities.

The classification results obtained on the 10 class problem are shown in Table 2. First, note that most of the defect classes contain only a limited number of samples. However, the results should at least be a reasonable approximation of that obtainable in the industrial environment.

Observe that six of the 10 classes have classification accuracies above the 68 percent range. Next, observe that one of the four below 68 percent, namely the hole defect class, used only two samples in calculating the result. There were more holes than that in the data, however, they were frequently labeled as background by the Node 1 logic. This was considered an acceptable outcome for purposes of this analysis. Hence the detection of holes was quite good.

Next note that three of the classes have classification accuracies below 30 percent. Clearly such accuracies are unacceptable.

Summary and Conclusions

The 94.6 percent rate, on the clear wood versus defect classification, would seem comparable to that of humans during the course of the normal work day. This is particularly true considering the hot working environment and the fatigue a worker experiences having to move boards about all day.

Unfortunately, to-date work performances on this problem are not well documented. Note, again, that the 94.6 percent rate was achieved using a computationally inexpensive technique so commercial implementation would seem feasible.

As to the 10 class problem, it is clear that current performance is not up to industrial requirements. The results for 7 of the 10 classes are very encouraging, though not up to commercial standards. Obviously three of the classes are problems and need significant improvements in accuracy. However, it is of interest to note that of 1,326 regions only 212 were mis-classified, or only 16 percent of the samples.

Given the need for further research the obvious thing to consider is color information. Research using color is currently underway.

REFERENCES

Conners, R.W., C.W. McMillin, K. Lin and R. Vasquez-Espinosa. Identifying and locating surface defects in wood--Part of an automated lumber processing system. To be published in the IEEE Trans. Pattern Analysis and Machine Intelligence.

Morrison, D.F. 1967. Multivariate Statistical Methods. McGraw-Hill, New York.

Haralick, R.M., K. Shanmugan, and Its' Hak Dinstein. 1973. Textural features for image classification. IEEE Trans. Systems, Man and Cybernetics. SMC-3(6):610-621.

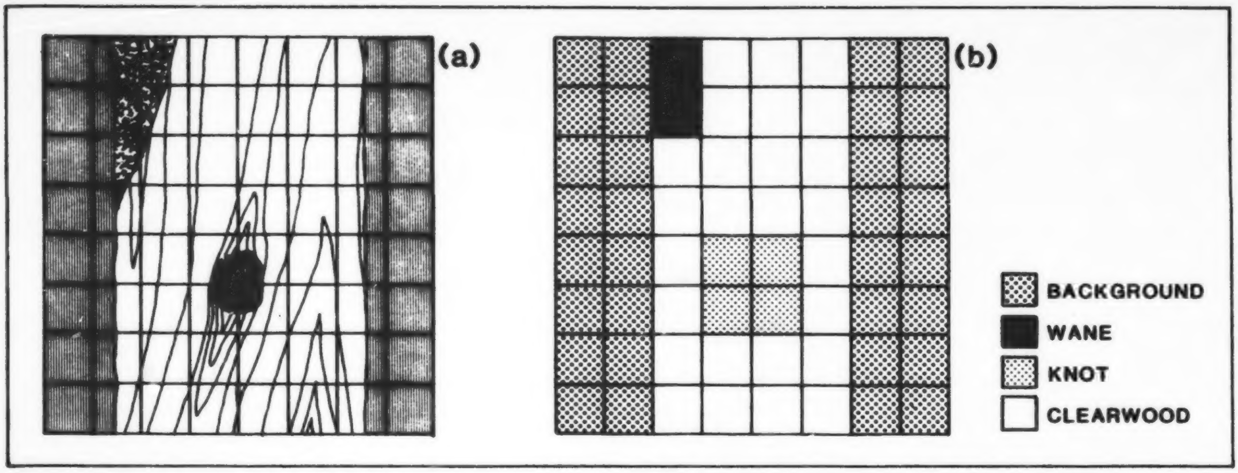
(a)
(b)
BACKGROUND
WANE
KNOT
CLEARWOOD

Figure 1. The input to the prototype system is a 512 x 512 x 8 bit image. The system divides this image into 64 mutually disjoint regions each 64 x 64 as is illustrated in Part (a). Part (b) indicates the desired output for the image of Part (a).

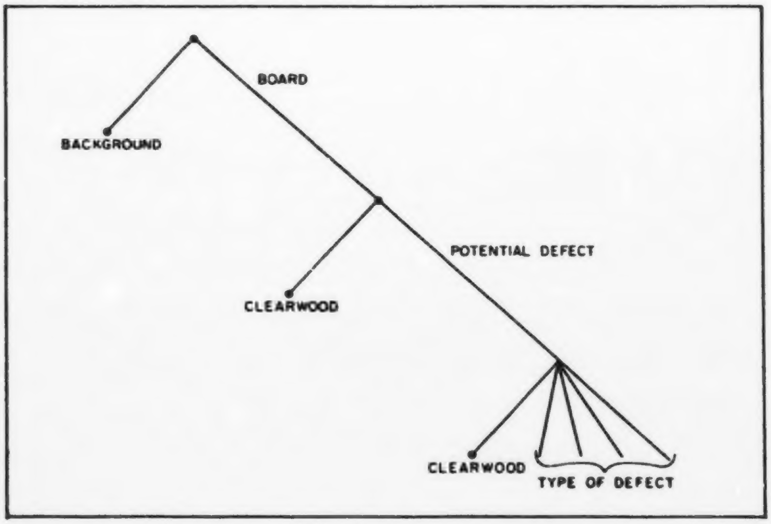
BOARD
BACKGROUND
POTENTIAL DEFECT
CLEARWOOD
CLEARWOOD
TYPE OF DEFECT

Figure 2. The sequential classification strategy used to minimize the computational complexity of the analysis. Node 1 separated regions containing only board from those comprised all or in part of background. Node 2 separated clear wood from potential defects. Finally, Node 3 attempts to classify the type of defect present.

		COMPUTER CLASSIFICATION			
		CW	DF	TOTAL	PERCENT CORRECT
VERIFIED CLASSIFICATION	CW	931	46	977	95.3%
	DF	21	328	349	94.0%
	TOTAL	952	374	1326	
		OVERALL PERCENTAGE CORRECT CLASSIFICATION			94.6%

Table 1

Results of the two class problem clear wood (CW) versus defect (DF). Note these results were obtained using only the computationally simple mean, variance and skewness measures.

		COMPUTER CLASSIFICATION											
		DE	KN	WN	ST	HL	SCH	MS	LB	DB	CW	TOTAL	PERCENT CORRECT
VERIFIED CLASSIFICATION	DE	71	10	0	3	1	0	0	3	0	0	38	80.7%
	KH	1	27	1	0	1	1	0	1	0	0	32	84.4%
	WN	0	11	6	1	7	2	0	6	2	0	35	17.1%
	ST	7	7	6	31	3	0	3	35	1	20	113	27.4%
	HL	0	0	0	0	1	0	0	0	1	0	2	50.0%
	SCH	0	0	0	0	0	14	1	0	2	1	18	77.8%
	MS	1	0	1	0	2	0	17	1	1	0	23	73.9%
	LB	0	0	0	3	0	1	0	11	0	1	16	68.8%
	DB	0	9	2	0	6	0	0	0	5	0	22	22.7%
	CW	20	1	0	1	0	9	6	6	3	931	977	95.3%
	TOTAL	100	65	22	39.	21	27	27	63	15	953	1326	

Table 2

The results of the 10 class problem. The 10 classes are decay (DE); knots (KN); wane (WN); holes (HL); split or check (SCH); mineral streak (MS); light bark (LB); dark bark (DB); and clear wood (CW). Note only about 16 percent of the samples were misclassified.

Use of Computers for an Automated Lumber Processing System (ALPS)*

R.W. Conners, K. Lin and D. Middleton

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Computers are needed in the ALPS system to analyze digital image data to locate defects, to compute an optimal sawing strategy to cut out the desired parts, and to control the conveyors and lasers used to move and cut up the boards. Of these tasks the most computationally complex are the image analysis function and the determination of the optimal sawing strategy. For example, to meet the necessary processing rate the computer system must obtain and analyze at very minimum 700,000 pixels (i.e., bytes) per second just to do the image analysis tasks.

Assuming that it takes at least three machine instructions to classify each pixel (and this is a very minimal estimate) this implies that the system must be capable of executing at least 2,100,000 instructions per second. The number of instructions per second needed to perform the sawing strategy are equally as large.

If an SISD (single instruction stream, single data stream) processor were used in ALPS a large mainframe computer would be required, the cost of which, even including expected decreases in price, would be prohibitive. Fortunately, the two most computationally complex problems lend themselves to parallel processing solutions. This means that a number of slower processors can be used; the sum total of whose efforts are 4,000,000 instructions per second.

While the parallel processing approach seems the only alternative, the possibility of using it depends on the research and development time needed to create such a system. Seemingly, to make this approach practical requires that off-the-shelf hardware be available which only requires a minimum of system integration and that methods be available to program the resulting system in a higher level language in order to reduce software development cost. Note that the software costs could easily make 80 percent of the total data processing component price of ALPS.

Given the ambiguity of the processing requirements the technological assessment of computers capable of meeting ALPS requirements will be based on demonstrating a currently available processor which seemingly has all the desired properties. The processor to be discussed is the new Intel iAPX-432 microcomputer (Hemenway and Grappel, 1981; Intel Corp, 1981a, 1981b, 1981c; Rathner and Cox, 1980). It represents the first of a new generation of microcomputers and seems ideally suited to the processing requirements posed by an ALPS type system.

**Extracted from "The Feasibility of an Automated Lumber Processing System for the Rough Mill Department of the Furniture Industry. Richard W. Conners, Kingyao Lin and Don Middleton, in cooperation with Charles W. McMillin (Southern Forest Experiment Station, Pineville, LA)*

If the past is any indication, as this new generation evolves marked improvements in processing power should become a reality within the next four to five years. Hence it seems that even if the initial iAPX-432 systems cannot meet the processing demands, improvements to this and/or processors marketed by other companies should.

The key features of the 432 system are its 32 bit architecture and the fact it was designed to support modular development of software in a high-level language--all important if tolerable software costs are to be achieved. This last point is possible because the 432's instruction set is designed to allow efficienct translation of high level language into machine-language programs.

In many cases, high-level instructions are translated into a single machine instruction instead of six or more instructions, as would be necessary on other machines. Such efficiency allows the use of a high-level language without incurring a penalty in speed or memory space--a factor that has discouraged the use of high-level languages in previous microprocessors.

The high-level language meant to be used with the 432 is Ada. Ada is considered the most sophisticated general-purpose language yet developed. It was specifically designed to support modular development for real-time applications.

The 432 also has operating system kernel in hardware. This kernel includes many of the basic operating system functions, such as task scheduling. This not only speeds execution but also cuts the time to develop specialized operating systems because a developer can build his operating system on top of the basic kernel.

To support parallel processing the 432 features a two-level multiprocessor bus structure. Using this bus structure, processors can be added to the bus to boost processing power without reprogramming. This very important feature which would markedly help in developing the parallel processing capability for the ALPS will be discussed in greater detail later.

First, however, it is important to examine the components comprising a 432 system. The basic iAPX 432 processor/interface consists of three 64-pin IC packages. The general data process (GDP) consists of two chips, the iAPS 43201 and the iAPX 43202. The first functions as an instruction decoding unit; the second a micro-execution unit. These devices communicate with one another across a directional 'micro-instruction bus'; together they fetch, decode and execute program instructions.

The third device in the set, the iAPX 43203, is the interface processor. It provides a link between the iAPX 432 system and an attached processor, connecting to the attached processor via a subsystem bus and communicating with the GDP via a 'packet bus' as shown in Figure 1.

The packet bus (i.e., the processor-to-process on bus discussed above), a time-multiplexed interface, provides communication between the iAPX 432 processor and memory, as well as between processors. This interconnection is illustrated in Figure 2. It is this packet bus which allows system expansion without software modifications.

The expansion is accomplished by merely adding more GDP chip pairs to the bus as is illustrated in Figure 3. This can increase system performance from 200,000 instructions per second to 2,000,000 instruction per second. This increase is obtained without any software changes. To obtain a 4,000,000 or more instructions per second capability requires only that one interconnect two or more groups of 432 using the multi bus (Figure 1).

Another very important feature of the 432 which makes it ideal for industrial automation problems is the ease with which it allows hardware failures to be detected. Obviously one does not want a computer to ruin good materials in case of a hardware failure.

With the 432-based system hardware failures can be checked by wiring two identical iAPX 432 processors together in a self-checking configuration (Figure 4). The devices run at full speed and check for on-chip defects as well as connection flaws. If the processors do not agree on a computational result, they stop and alert the rest of the system that they can no longer guarantee correct operation.

The last important feature of the 432 is that it can address a gigantic amount of memory (2^{24} or 16,000,000 segments each of which can contain 2^{16} bytes). This ability is very important in that it allows DMA transfers and storage of large image arrays while processing is occuring. This is very important if one has to quickly obtain and analyze an image.

Given the capability of the 432 system, a system which is commercially available today, it seems improbable that the processing requirements of ALPS cannot be met by processors within the next five years.

One other important point should be made. The cost of main memory should continue to fall during the next five years. Currently, 64 K RAMS are commercially available. However, the full economic impact of these devices on memory prices has not been felt. Also, 256 K RAMS are being developed and quality devices should be commercially available in two to three years. The advent of these devices should further depress memory prices.

Hence from the computing point of view the technological feasibility of an ALPS system seems assured.

Hemenway, J. and R. Grappel. 1981. Intel's iAPX 'Micromainframe'. Mini-Micro Systems. May:73-87.

Intel Corp. 1981a. Introduction to the iAPX Architecture. 171821-001. Intel Corp., Santa Clara, CA.

Intel Corp. 1981b. iAPX 432 GDP Architecture Reference Manual. 171860-001. Intel Corp., Santa Clara, CA.

Intel Corp. 1981c. iAPX 432 GDP Object Primer. 171858-001. Intel Corp., Santa Clara, CA.

Rathner, J. and G. Cox. 1980. Object based computer architecture. Computer Architecture News. Oct.:

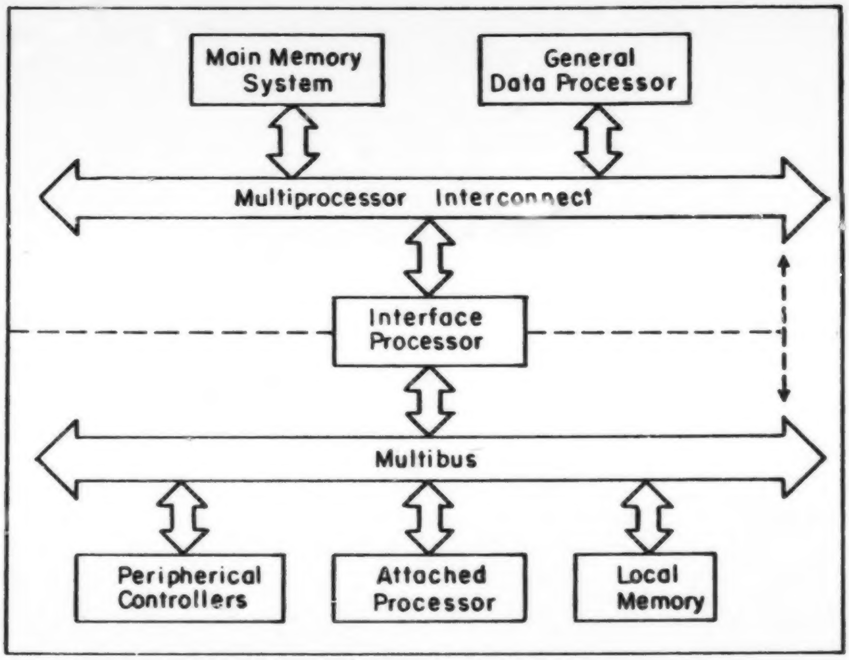
Main Memory System
General Data Processor
Multiprocessor Interconnect
Interface Processor
Multibus
Peripherical Controllers
Attached Processor
Local Memory

Figure 1. A satellite subsystem (attached processor) can independently handle all I/O with the aid of multibus

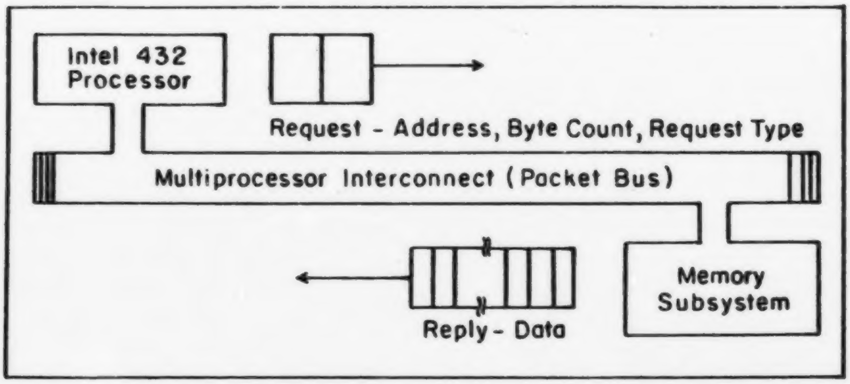
Intel 432 Processor
Request - Address, Byte Count, Request Type
Multiprocessor Interconnect (Packet Bus)
Memory Subsystem
Reply - Data

Figure 2. The 432's packet bus can transfer as many as 16 bytes of data with a single request

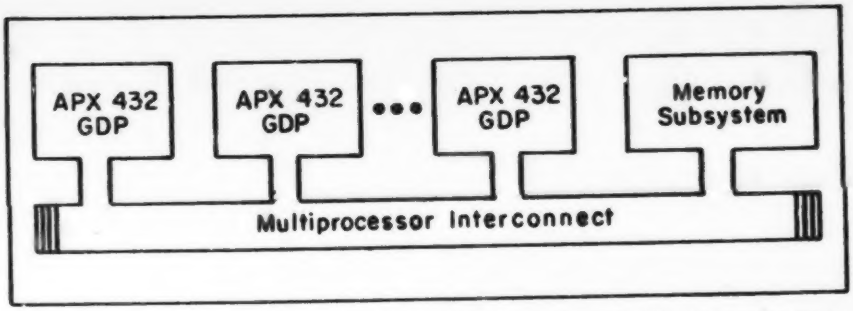
APX 432
GDP
APX 432
GDP
•••
APX 432
GDP
Memory
Subsystem
Multiprocessor Interconnect

Figure 3. Transparent multiprocessing requires no software changes as data processors are added to a 432-based system

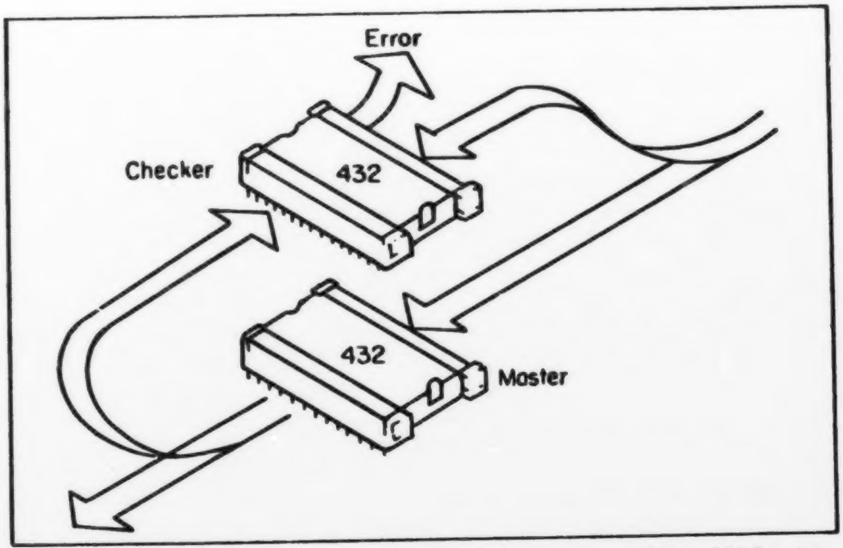
Error
Checker
432
432
Master

Figure 4. Functional redundancy checking allows two iAPX 432's to check one another and flag computational errors

Optical Scanning Technique for Defect Detection

J. Soest, Weyerhaeuser Technical Center, Tacoma, WA

A number of non-contacting measurement techniques have been used to find and measure the extent of biological defects (knots, decay, etc.) in solid wood products, including visible and laser light scanners, acoustic waves, microwaves and gamma rays (Szymani and McDonald, 1981).

PROBLEM STATEMENT-- SCANNING FOR DEFECTS IN SOLID WOOD PRODUCTS

Find, identify, and measure a large category of defects in a material that has a wide range of natural variation.

- with high measurement precision
- at current production speeds or better
- with accuracy at least as good as the current (human visual) process

There would be high value in automating the detecting function in a wide range of lumber and plywood applications, where this function is now carried out by human observation and decision.

SOME POTENTIAL APPLICATIONS FOR A WOOD SCANNER

- selection of prime material for high value use (furniture, window moulding, laminated beams)
- cutting out defects to manufacture clear material
- automation of the visual grading process for common lumber
- optimization of other sawmill functions

SPECIFIC EXAMPLE--
VISUAL GRADING PROCESS FOR COMMON LUMBER

- human grader decides a grade category and the optimum length for each board
- categories are established by national grading rules
- piece rate is typically one board every two seconds
- grader must look at all four sides

For reasons of resolution, high process speed requirements, sensitivity, and safety, optical scanners are probably the technique of choice, at least for finding defects at or near the surface of the wood. One optical scanner has been constructed and used in a special application in a molding plant (King, 1978), but no other successful mill operation of optical defect scanners is known.

Several groups have suggested using video or area array scanners to gather data followed by image processing techniques to locate and classify defects (Conners et al., 1983). However, these techniques currently require far more processing time than is available at existing piece rates for most applications.

DATA RATE PROBLEM
(FOR AN AUTOMATED SYSTEM)

- pixel size of 3/4 mm across board by 3 mm along board
- longitudinal feed rates up to 6 m/second
- board piece rate typically one per second
- thus data rate (collect AND PROCESS) is on the order of one million pixels per second

A fundamental breakthrough was achieved when it was discovered that light focused to a point on a softwood surface is scattered preferentially in the grain direcion, if the grain is undisturbed by defects (Mathews and Beech, 1976). This property is called the "tracheid effect", after tracheid cells in softwoods.

TRACHEID EFFECT

- anisotropic scattering and transmission of light in softwood cells
- provides fundamental discrimination between defective and clear wood

Detecting the presence or absence of this scattered light leads to a method for discriminating between good wood and defective wood on a point-by-point basis, with no reference to the quality of the surrounding points. The effect of the laser beam scattering is shown in Figure 1 (plate 3) for a knot, compression wood, blue stain, rot and good wood.

Weyerhaeuser and Plessey controls have constructed a laser-based scanner using this method that can operate at high speed (linear feed speed of 6 m/sec) with high resolution (0.75 mm in the scan direction by 3.1 mm in the feed direction). In addition to the tracheid effect signal, color and laser retro-reflection signals are collected in order to aid in the identification of the defect type.

A laboratory development system was constructed to study the signals from a wide range of materials and defects, in order to specify the optimal signal processing steps that will lead to the identification and measurement of the defects. These processing steps are carried out now in an off-line mode, but have been constructed consistent with the goal of duplication in simple real-time signal processing hardware.

An example of the output from the system, identifying knots and compression wood, is shown in Figure 2 (plate 3). On the left are the defect and clear wood designations, the color identification of each pixel is in the center and the final interpretation is on the right. Another example (Figure 3, plate 3) indentified rot and blue stain.

The third example (Figure 4, plate 3) shows the system being applied to a lumber grading decision. On the left is the color identification of the different grades. On the right is the final interpretation showing the cutting pattern required to produce boards of specific grades from a typical board showing wane and knots.

In comparison to positioning by a grader, the accuracy of positioning defects by a scanner is quite good. Figure 5 shows an average deviation of ± 1 mm for face knots with a standard deviation of ± 4 mm. A similar study for spike knots showed an average scanner deviation of ± 2 mm for spike knots with a standard deviation of ± 3 mm.

A planer speed prototype needs to be developed from this system, as well as hardware to replace the algorithm used for interpreting the defects.

References

Syzmani, R. and K.A. McDonald. 1981. Defect detection in lumber: state of the art. Forest Prod. J. 31(11):34.

King, E.A. 1978. Laser scanning. Proc. of the 4th Nondestructive Testing of Wood Symposium, Vancouver, WA. pp.15-22.

Conners, R.W., C.W. McMillin, K. Lin and R.E. Vasquez-Espinosa. 1983. Indentifying and locating surface defects in wood--Part of an automated lumber processing system. IEEE Transactions on Pattern Analysis and Machine Intelligence, PAMI-5, 573.

Mathews, P.C. and B.H. Beech. 1976. Method and Apparatus for Detecting Timber Defects. U.S. Patent No. 3,976,384.

Acknowledgment

Essential contributions were made to this work by E.A. Olmstead, Project Manager, Weyerhaeuser Canada Ltd., from 1979 to 1983; P.C. Matthews, Research Manager, Plessey Controls Ltd.; and C.F. Horn, Project Technician, Weyerhaeuser Canada Ltd.

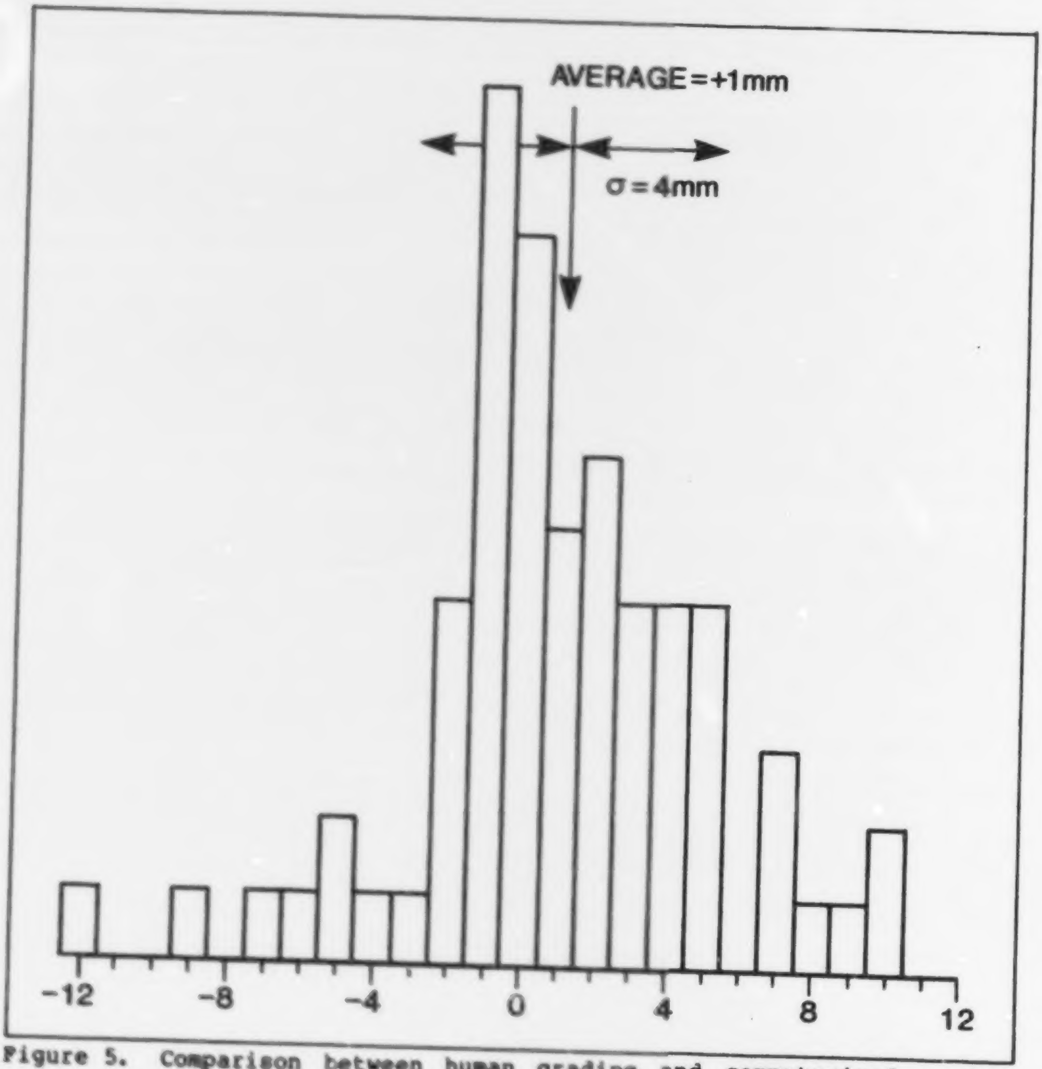

Figure 5. Comparison between human grading and computerized grading decisions for face knots.

Automation of Lumber Defect Detection

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As a natural material, wood has high inherent variability, both between and within species. This can cause wide deviation in the properties of individual pieces. Any characteristics that make wood suitable for a given use, such as irregularities in the fibrous structure, are understood here to be natural defects.

Defects: Definition and Classification

There are defects resulting from wood characteristics such as cross grain, knots, and pitch, as well as defects caused by wood-destroying and wood-staining fungi and true moulds (e.g., white and brown rots, sap stains, etc.), and deterioration caused by insects.

The manufacturing process can also cause lumber defects from sawing inaccuracy (e.g., size deviation) and material handling practices (e.g., forklift damage). For the purpose of this discussion, wood defects will be grouped into two classes:

- Biological defects (natural defects, defects caused by wood-destroying and wood staining fungi, and deterioration of wood caused by insects), and
- Manufacturing defects (defects caused by sawing, seasoning, planing, and material handling practices).

Defect Detection System Requirements

There is a need, in general, for an on-line operating automatic system for sensing, classifying, and measuring the size and relative position of defects within a log or board. The information obtained should be in a form suitable for computer processing. This would allow optimizing subsequent cutting, grading and sorting decisions. A computer controlled mechanical system can, in turn, be programmed to operate on either a maximum value or volume recovery basis.

The performance requirements for an automated defect detection system for lumber include:

- Consistent and reliable operation
- Real-time scanning capability and sensitivity to changes in external and
- internal log or lumber characteristics
- Insensitivity to industrial environment
- Cost effectiveness and ease of maintenance
- Built-in diagnostics and alarm
- Backup system
- Freedom from radiation hazards to operator.

Performance requirements will differ from one application to another (Table 1). The system supplier should assist the user in mill startup and debugging, as well as providing operator and supervisor training.

DEFECT DETECTION METHODS AND THEIR POTENTIAL FOR ON-LINE APPLICATION

Optical Method

There are two optical techniques used for defect detection. One technique uses a laser beam as a light source. The beam (approximately 1 mm in diameter) is directed at a scanning mirror that plays it back and forth across the object under inspection. This provides a line scan at the right angles to the motion of the object. Scans must be taken at close enough intervals to assure that any change is a trend and not a singular incident.

The second technique utilizes flourescent light that illuminates the entire board as it moves past the scanning station. This technique is used for determining board geometry (wane) and detecting defects. At the same time, it allows optimization of subsequent edging and/or cut-up decisions.

Laser Scanning Method

In 1981 there were two laser systems used for defect detection. They were:

- The laser scanner and automatic cut-up system, developed by Bendix Research Laboratories and Bendix Forest Products Co.* of San Francisco. CA, and
- The Plessey optical defect detection apparatus being developed by the Plessey Co., Ltd. of Essex, England in cooperation with Weyerhaeuser Co., Tacoma, WA.

Laser light reflected from the wood is detected by photomultiplier tube assemblies. Resultant signals are quantified and digitally processed before being transmitted to the minicomputer. The minicomputer software processes and filters the incoming data, calculates the size and locations of defects, and determines the optimum cutting pattern. The computer then commands two automatic saws (one fixed and one movable) to crosscut the board and remove defects. The cutting rate is about 100 feet per minute (King, 1978 and 1979).

The laser scanner can detect splits, checks, and red (tight) and black (loose) knots of varying sizes. The lighter colored flaws and certain types of edge grain, however, have proven difficult to detect (King, 1978 and 1979) and acceptable blemishes are sometimes detected as defects. The automatic cut-up system has been in operation for two years.

The other detection and cut-up system and method is described in detail in the patents of Matthews and Beech (1976 and 1977).

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*Now the American Forest Products Corp.

Detection and limited differentiation of defects such as knots, blue stain, and certain kinds of rot are achieved by a laser scanner and suitable photodetectors and filters.

Fluorescent Light Scanning System

An automatic scanning system that utilizes fluorescent light and makes complete evaluation of the board is the Iggesund's opti-edger (Lakatosh, 1966). It is used to determine both board geometry and defects--wane, knots, and other characteristics which may affect the quality definition. The basic features and operational principles of the Iggesund opti-edger are schown schematically in Figures 1 and 2.

The operation of the opti-edger is similar to the edger optimizer (Szymani, 1979). The opti-edger analyzes each board with the aid of cameras (Figures 1 and 2). The detected variations on board quality are registered in a computer in which both grading criteria and prices of all sizes and grades can be entered via a keyboard. The computer operates an automatic control and feed system which performs the edging procedure determined by the system.

Ultrasonic Method

Among nondestructive evaluation (NDE) methods, only ultrasonics and electromagnetic methods have the potential to reveal defects which are not visible on the surface. Because the propagation of ultrasound is essentially a mechanical phenomenon, it is especially suited to determining the characteristics of materials such as wood products (Burmester, 1965; Lakatosh, 1960; Lee, 1958; Sumiya, 1965 and Szabo, 1978).

A major limitation of ultrasonic testing is the difficulty it poses for continuous scanning over the surface of the test specimen. Transducers must be adequately coupled to the material being tested. This implies physical contact or use of a suitable couplant. Therefore, when continuous scanning of a large surface area is required, immersion testing is usually used. In this method, the article being scanned is immersed in a tank of water. A submersible transducer is placed near the piece; the water serves as the ultrasonic couplant.

Experimental Ultrasonic System for Lumber

The first computer controlled inspection system which uses ultrasonics was developed by the U.S. Forest Products Laboratory in Madison, WI (McDonald, 1971, 1973, 1976, 1978 a and b, 1979; McDonald and Cox 1972; McDonald et al., 1969; and McDonald and Syzmani, 1980). This laboratory system (defectoscope) was designed as a prototype to model critical parameters associated with automatic defect detection in lumber and subsequent computer aided cut-up decisions.

The inspection system (Figure 3) is based on the through-transmission technique. Frequencies used range from 150 kHz to 1,000 kHz. The higher the frequency, the greater will be the inspection precision (McDonald, 1976 and 1978). Transit time data from each board is recorded to the nearest 0.01

microsecond and is stored in the computer for analysis after scanning is complete. A sample contour plot of data actually collected is shown in Figure 4 (top). It indicates the strong correlation between the visible grain pattern of the scanned board and the transit times. The sawing algorithm selected for demonstration (Figure 4) (bottom) simulates a finger-jointing operation producing the maximum yield of wood moldings.

Advantages and Limitations

The ultrasonic technique can be used to locate defects in lumber. Based on the anisotropic properties of wood with respect to sound, this technique differentiates straight-grained, sound wood from localized steep grain areas around the defects. In the case of advanced decay, ultrasonic signals will be substantially attenuated. Thus, the technique is most promising for detection of knots, rot and pitch pockets.

Certain defects such as small cracks, splits and checks, and grub and worm holes are not reliably detected by this technique. Furthermore, this technique does not detect spiral grain, an important defect in assessing structural wood quality, or wood discoloration.

Due to these limitations, ultrasonics should be used in combination with optical techniques in order to assure a comprehensive on-line inspection of lumber.

X-ray Method - Application of X-rays

The use of X-ray radiography for detecting defects such as rot and insect damage dates back several decades (Maloy and Wilsey, 1930; Zucker, 1940). It was discovered that such wood defects could be readily detected when the change in wood density was sufficient to reduce absorption of X-rays.

In spite of those early investigations, X-ray radiography has not been used to any large extent in the wood industry, largely due to the cost and inconvenience of using X-ray film.

Special Radiography: X-ray Fluoroscopy and Tomography

Fluoroscopy is a direct conversion of X-ray patterns to visible light patterns by means of a fluorescent (phosphorus) screen. The phosphor, when stimulated by X-rays, emits visible radiation (light) of an intensity proportional to X-ray intensity. The results obtained by Muller (1964) have shown that X-ray fluoroscopy provides a rapid, nondestructive method for detecting internal defects. Voids as small as 1/2 inch in diameter, due to rot pockets or other causes, could be detected in green softwood lumber two and three inches thick.

The results also established that decayed areas in samples of dry wood were clearly visible in the images produced by X-ray fluoroscopy. Apart from the detection of rot, fluoroscopy has the potential of detecting metal objects in saw logs and veneer logs.

It is also possible to examine the interior of a wood specimen using a Computerized Axial Tomography (CAT) scanner (Schmidt, 1978). Combining X-ray equipment, a computer, and a television cathode ray tube, this medical diagnostic device can also reveal various internal wood defects. (Figures 5 and 6)*. The exposure time (Figure 5) was 37 seconds; the computer took about two minutes to generate the resultant picture (Figure 6). However, the present high cost of the CAT systems precludes their use in the wood industry.

Conclusion

Based on the foregoing evaluation and according to the comparison of selected lumber defect detection methods, the following observations are made:

- Optical scanning methods are limited to the detection of defects visible on the surface of the lumber. These methods do not differentiate between defects except for the partial differentiation offered by the Plessey scanner. Since the detection of defects is primarily based on the variation in the amount of reflected light, surface characteristics such as heartwood-sapwood contrast could be confused with actual defects. Other defects which have insufficient color contrast with surrounding clear wood tissue can escape detection by optical scanning. Therefore, in the above cases the lumber defect detection system requires manual suppression or enhancement of its detection capability.

- The ultrasonic and X-ray methods are capable of detecting internal defects, but will not detect any wood discoloration. The most promising internal defect detection method is ultrasonic sensing. A major disadvantage is that the ultrasonic transducers must be mechanically coupled with the material being tested by submersion of the wood in water. The disadvantage of microwaves, X-rays, and neutrons is that their detection capabilities may be affected by variations in wood density and moisture content, particularly in green lumber.

- Since a defect detection system must be sensitive to changes in both external and internal qualities of lumber in order to assure a comprehensive online inspection, optical methods should be used in combination with one other internal defect detection method. In a sawmill the lumber defect detection and subequent rip or crosscutting could be done in conjunction with the automated edging operations.

- An efficient lumber defect detection system is a valuable tool in increasing mill profits. The expected gains in yield are substantial (as high as 10 percent) depending on current mill practices and the degree of automation. The maximum yield for a given product must be determined in order to justify automation of defect detection at a cost effective level.

**Schmidt, T. 1969. Swedish Forest Products Laboratory, Stockholm, Sweden.*

References

Burmester, A. 1965. Relationship between sound velocity and the morphological, physical and mechanical properties of wood. (In German.) Holz Roh Werkst. 23(6):227-236.

King, E.A. 1978. Laser scanning. Proc. 4th Nondestructive Testing of Wood Symp., Vancouver, WA. August 28-30, 1978. pp. 15-22.

King, E.A. 1979. An operating defect detector. Presented at the North American Sawmill and Plywood Clinic, Portland, OR. March 7-9, 1979.

Lakatosh, B.K. 1960. Defectscopy of wood. (Translated from Russian). Lesn. Prom. 121-177.

Lee, I.D.G. 1958. A nondestructive method for measuring the elastic anisotropy of wood using an ultrasonic pulse technique. J. Inst. Wood Science. 1:43-57.

Maloy, T.P. and R.B. Wilsey. 1930. X-raying trees. Am. For. and For. Life. 36(2):79-82.

Matthews, P.C. and B.H. Beech. 1976. Method and Apparatus for Detecting Timber Defects. U.S. Patent No. 3,976,384. August 24, 1976.

Matthews, P.C. and B.H. Beech. 1977. Improvements In or Relating To Optical Detection Apparatus. British Patent No. 1,488,841. October 12, 1977.

McDonald K.A. and R. Szymani. Lumber defect detection using ultrasonics, microwaves and X-rays. (In French.) Proc. of the Symp.: Silviculture through Logging to our Industrial Raw Material. Cent. Tech. du Boise, Paris, France. November 27-28, 1980.

McDonald, K.A. 1971. Locating Defects in Softwood Lumber. MS Thesis, Univ. of Wisconsin, Madison, WI.

McDonald, K.A. 1973. Ultrasonic location of defects in softwood lumber. Timber Trades J.

McDonald, K.A. 1976. Ultrasonic recognition of lumber quality. Proc. Forest Prod. Res. Soc., Northern California Section, Sacramento, CA. May 20-21, 1976. pp. 3-5.

McDonald, K.A. 1978a. Lumber Defect Detection by Ultrasonics. U.S. Forest Prod. Lab., Madison, WI. Res. Pap. FPL 311.

McDonald, K.A. 1978b. Lumber quality evaluation using ultrasonics. Proc. 4th Nondestructive Testing of Wood Symp., Vancouver, WA. August 28-30, 1978. pp 5-13.

McDonald, K.A. 1979. Application of Ultrasonics in the Wood Industry. Proc. Ultrasonics International 1979, Gratz, Austria. May 15-17. pp. 360-365.

McDonald, K.A. and R.G. Cox. Ultrasonic Detection of Lumber Defects. U.S. Patent No. 3,664,180. May 23, 1972.

McDonald, K.A., R.G. Cox. and E.H. Bulgrin. 1969. Locating Lumber Defects by Ultrasonics. USDA Forest Serv. Res. Pap. FPL 120.

Müller, D.G. 1964. Detection of rot in wood by electronic X-ray fluoroscopy. B.C. Lumberman. 48(10):64-67.

Schmidt, T. 1978. Scanning/computer methods for measuring knots and other defects in lumber and veneer. Proc. 4th Nondestructive Testing of Wood Symp., Vancouver, WA. August 28-30, 1978. pp. 23-25.

Sumiya, K. 1965. Relations between defects in wood and velocity of ultrasonic wave. Wood Res. Inst., Kyoto Univ., Kyoto, Japan. Wood Res. (34):23-36.

Szabo, T. 1978. Use of ultrasonics to evaluate or characterize wood composites, Proc. 4th Nondestructive Testing of Wood Symp., Vancouver, WA. August 28-30, 1978. pp. 239-260.

Szymani, R. 1979. Technology of optoelectric scanning in sawmilling. Proc. 6th Wood Machining Seminar, Univ. of California Forest Prod. Lab., Richmond, CA. October 15-17. pp. 119-138.

Zucker, M. 1940. The technique of inspecting wood poles by X-rays. ASTM Bull. 106:19-26.

Table 1

Comparison of Selected Defect Detection Methods

GENERAL CLASSIFICATION OF DEFECT DETECTION METHODS (major variation in methods)	PROPERTIES SENSED OR MEASURED	Lumber defects detected[a]													ADVANTAGES	LIMITATIONS
		Biological								Manufacturing						
		Knots	Cross grain	Rot	Stain	Holes	Pitch poc.	Bark incl.	Pith	Wane	Torn grain	Split	Checks	Size dev.		
OPTICAL (reflection or through-transmission[b] of light)	Anomalies in light reflection or transmission	X		X	X	X	X	X	X	X[c]	X	X	X	X[d]	Detect defects visible on the surface, readily automated	Cost (laser scanner), poor differentiation of defects
ULTRASONIC (through-transmission or pulsed echo inspection)	Anomalies in accoust. impedance (energy transmitted or reflected) and ultrasonic transit time	X	X[e]	X[f]		X[g]	X	X	X	X	X				Excellent penetration, readily automated, good sensitivity and resolution	Requires mechanical coupling to surface (water immersion)
MICROWAVE (through-transmission or reflection)	Anomalies in dielectric properties and reflection or scattering of electro mag. waves	X	X[e]	X		X									Noncontacting, readily automated, rapid inspection	Comparatively poor differentiation of defects
X-RAY (film radiography, fluoroscopy, or scintillography)	Inhomogeneities in density, composition, or thickness	X		X[f]		X	X	X						X[h]	Detect internal flaws, instantaneous inspection, easily adapted to production line	Relatively insensitive to thin laminar flaws, poor diff. of defects, health hazard
NEUTRON (film radiography or scintillography)	Compositional inhomogeneities selectively sensitive to particular atomic nuclei	X		X[f]		X	X	X						X[h]	Quantitative real-time output, flexibility of sample size, high sensitivity, accuracy, & speed	Relatively insensitive to thin laminar flaws, poor diff. of defects, health hazard

[a] An X indicates that the defect has been detected by a given test method.

[b] Through-transmission of light is only suitable for thin sections (less than or equal to 1/4 in.) and can detect knots, holes, and pitch pockets above 1/4 in. in size.

[c] Using light shadow technique.

[d] Measured with the laser scanner.

[e] Localized steep grain.

[f] Advanced decay.

[g] Above 3/4 inch in diameter.

[h] Significant variation in thickness.

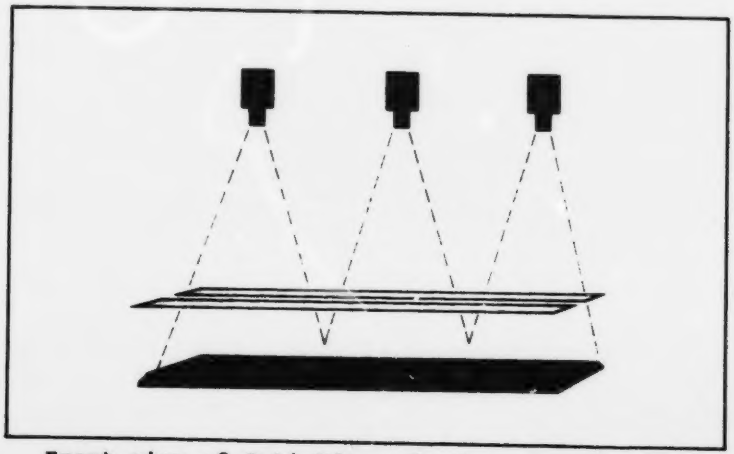

Figure 1. Front view of Opti-Edger showing cameras (top), light source (center), and board being scanned. (Courtesy of AB Iggesunds Bruk.)

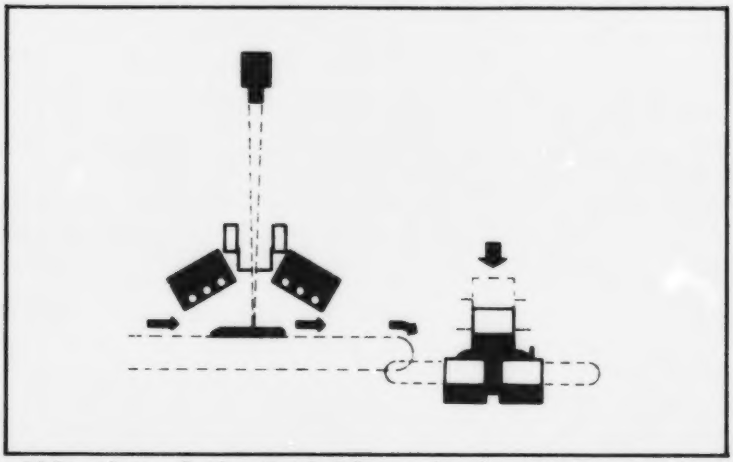

Figure 2. Side view of the Opti-Edger showing arrangement of lighting sources and the feed system. (Courtesy of AB Iggesunds Bruk.)

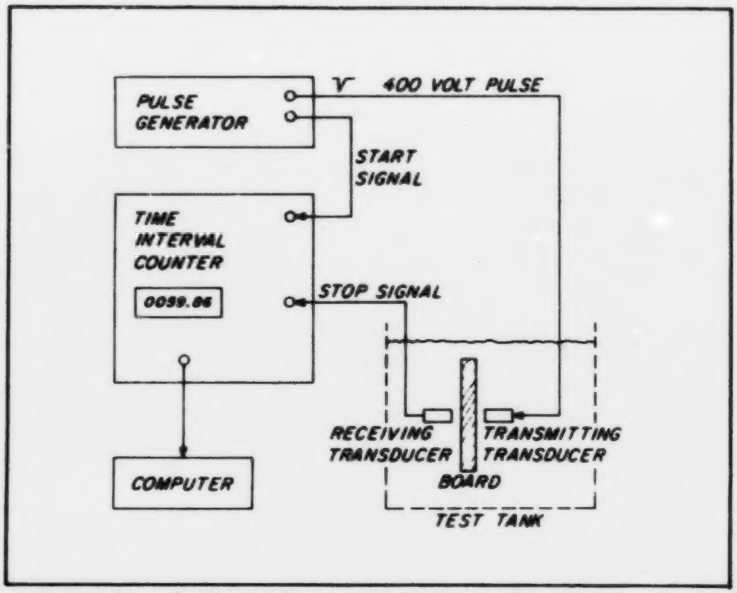
PULSE GENERATOR
400 VOLT PULSE
START SIGNAL
TIME INTERVAL COUNTER
0039.86
STOP SIGNAL
RECEIVING TRANSDUCER
TRANSMITTING TRANSDUCER
BOARD
TEST TANK
COMPUTER

Figure 3. Schematic of through-transmission ultrasonic technique used for transit time measurements. (Courtesy of U.S. Forest Products Laboratory.)

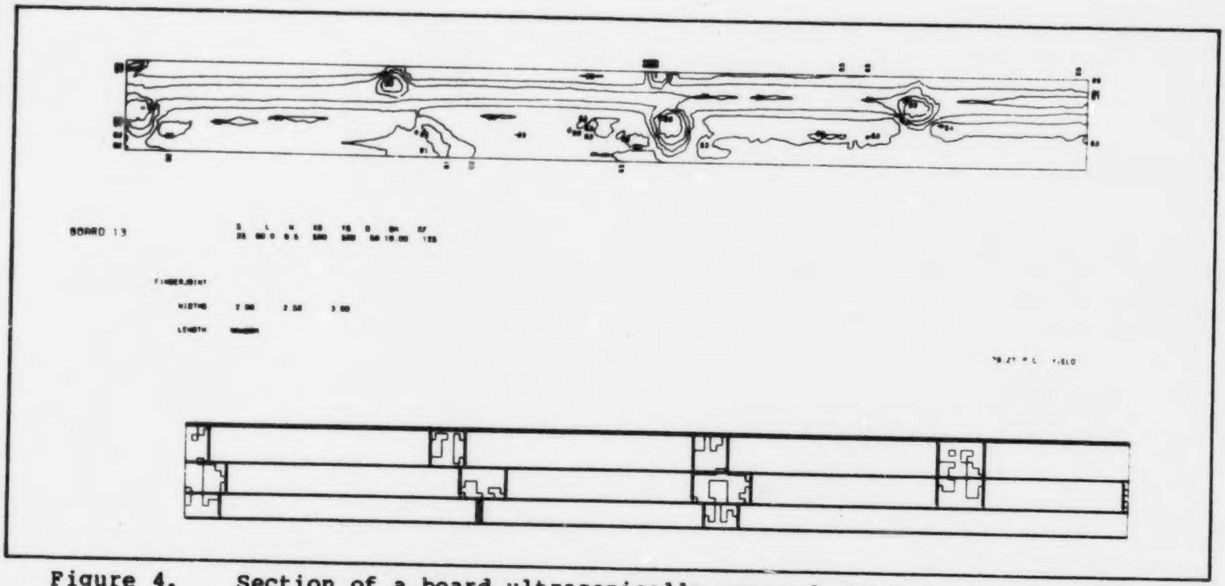

Figure 4. Section of a board ultrasonically scanned showing, top, contour plot of ultrasonic transit time data, and, below, defect analysis results and ripping and crosscutting solution for their removal.

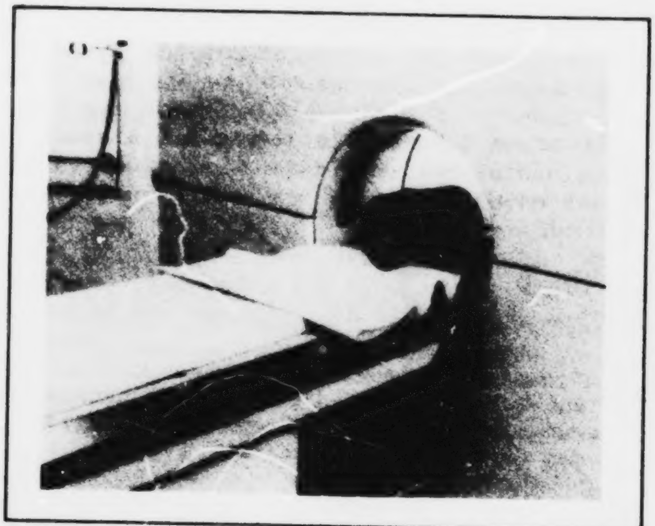

Figure 5. A spruce log being examined in a medical X-ray tomograph. (Courtesy of Swedish Forest Products Research Laboratory.)

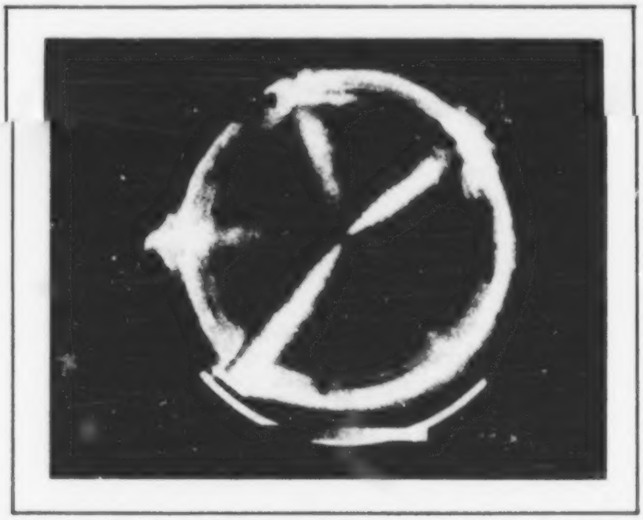

Figure 6. X-ray tomograph picture showing defects in the interior of the log. (Courtesy of Swedish Forest Products Research Laboratory.)

Closing Remarks

J.S. Swanson, Forintek Canada Corp., Vancouver, B.C.

I wrote down a number of items these past two days and amongst them were more than 56 terms used by various speakers that are not normally heard around saw mills. These included computer tomography, picture elements, X-ray transmission, projection radiography, super conducting magnets, threshold boundaries, ultra sound, reflection, electrical properties, molecular motion; such as molecular rotation, molecular stretching vibration; electro magnetic radiation, phase changes, polarization, fiber optics, scan density, linear arrays, photo diodes, lasers, charged coupled devices, solid state cameras, and electro optics. I also heard things I'd never heard before. These ideas and concepts made this program thought provoking, somewhat intriguing, and inspiring. The subject matters were complex, timely, technical, out of the ordinary and exciting. I have come away with a new idea of just what scanning is and what it means to us today. If we put these ideas together we can write a new definition of scanning. It goes something like this:

> Scanning is the rapid, automatic and precise location, identification, and measurement of chemical and physical properties throughout a material, in this case wood. Converting this information into digital form for analysis and applying artificial intelligence to use this information to control manufacturing processes for the optimum utilization of equipment and raw materials.

We have also identified the future potentials for scanning. We are going to see a lot more research and developments. We have just begun to scratch the surface, especially in the area of computers and artificial intelligence.

Before we leave, there are a couple of things I would like to do. First, I would like to thank the speakers that came and participated. The whole idea of this program was to encourage and provide a forum for technical exchange. It has not been one way, but truly a technical exchange as we had hoped. These last two days people have been getting together and talking about the ideas and concepts presented here, and that is the whole idea. As a result, I am sure we are going to see new research directions, and many new projects and developments.

I expecially acknowledge the hard work and effort of Joe Hailey who has worked for months to identify appropriate persons to participate, to contact them and to make all the arrangements for this program. Joe did an excellent job and deserves a lot of credit.

Finally I would like to thank the audience for coming and participating, I hope you have learned something, that you have been inspired and I anticipate doing something like this again in the near future, perhaps in another area affecting our industry.